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GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT ~~INITIATION~~ Reactivation

Date: October 14, 1974

Project Title: "SATRACK Missile Antenna Study" (Task 2 under this contract)

Project No.: A-1617-100

S

Project Director: J. W. Cofer

Sponsor: Applied Physics Laboratory, The Johns Hopkins University, Silver Sprg., MD

Effective March 13, 1974* Estimated to run until Sept. 26, 1975

Type Agreement: Contract No. 600128 (Subcontract under Gov't Prime N00017-72-C-4401; Amendment No. 5 Amount: $ 49,972.00*(New Task 2 effort

Reports Required: Monthly Progress Letters, Monthly Fiscal Reports; Final Comprehensive Report

Sponsor Contact Person (s):

Technical Matters
Dr. C. C. Kilgus
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Mr. K. H. Taylor
Contract Representative
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*Contr. Amend. No. 5 broadens Task 2 with new work partially funded at $25,000; total estimate for all Task 2 efforts is now $74,929.
DEFENSE PRIORITY RATING: DO-A2 under DMS Reg.1

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Date: July 15, 1976

No Prop. Actions -

B270 22 N-

Project Title: SATRACK Missile Antenna Study

Project No: A-1617-100

Project Director: Mr. J. W. Cofer

Sponsor: Applied Physics Laboratory; The Johns Hopkins University

Effective Termination Date: 9/26/75 (Task 2 completion date)

Clearance of Accounting Charges: 9/30/75

Grant/Contract Closeout Actions Remaining:

S

Documents charged to A-1617

X Final Invoice ~~and Closing Documents~~ for Task 2.
_ Final Fiscal Report
_ Final Report of Inventions
_ Govt. Property Inventory & Related Certificate
_ Classified Material Certificate
_ Other ____________________

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CA-4 (3/76)

A-1617-100

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

25 April 1974

Applied Physics Laboratory
Johns Hopkins University
Silver Spring, Maryland

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task II
(SATRACK Study)

Subject: Monthly Contract Technical Status Report No. 1
covering the period 14 February to 14 April 1974.

Dear Dr. Kilgus:

This is the first monthly progress summary under the referenced contract and covers the period 14 February to 14 April 1974.

During this report period, contract negotiations were completed and the subject base contract has been designated as Georgia Tech Project A-1617 (SEASAT). Amendment No. 1 (SATRACK) to the subject contract was added on 10 April 1974 with anticipatory charge clauses covering efforts back to 14 February 1974 and has been designated as Georgia Tech Project A-1617-100. Dr. D. G. Bodnar will direct all SEASAT efforts and Mr. J. W. Cofer, Jr. will serve as Project Director of the SATRACK effort. Both efforts will be executed within the Electromagnetics Program Office managed by Dr. D. G. Bodnar.

On 14 and 15 February 1974, Mr. J. M. Schuchardt of Georgia Tech visited APL to participate in a SATRACK system conference with APL, Navy, and Lockheed personnel. Data presented at this meeting indicated that the performance of the current designs of both the 150 and 400 MHz antennas are unsatisfactory.

On 27 February 1974, Messrs. J. W. Cofer and J. M. Schuchardt of Georgia Tech visited the facilities of Lockheed Missile and Space Company (LMSC) to discuss the program with Messrs. Jack Wade and Sid Altizer of LMSC. Several pertinent dimensions of the display mock-up were measured and documented. The radiation measurements model and the antenna range were also inspected.

Mr. J. W. Cofer visited APL on 19 March 1974 to attend an IEC system meeting and provide inputs to an antenna specification to be placed on LMSC. The format of this specification was written during this visit and was later completed by phone during a conference call among R. B. Hester, C. C. Kilgus, and E. E. Westerfield of APL and R. M. Goodman and J. W. Cofer of Georgia Tech. Essentially, the specification stated that the antennas would have gain levels of at least -13 dBi and -10 dBi at 400 MHz and 150 MHz, respectively, over 90 percent of a 4π steradian sphere.

During the first two months of the SATRACK program, most of the effort was directed toward the writing and verifying of computer programs which could calculate the total radiation distribution over all space from an arbitrary array of elements on a ring, plot the distribution of power in a number of graphic forms, and calculate the statistical distribution of the power pattern. These calculations can shed light on such factors as the number of elements needed and the effects of various phasings of these elements. In order to implement such numerical calculations, an element pattern which approximates that which could be obtained from a physical antenna must be selected. The drawback to the approach is that the computer technique cannot account for the fact that the vehicle carrying the element becomes energized, reradiates, and alters the assumed element pattern. As an example of such calculations, two elements having a cardioid power pattern were fed (assuming use as a transmitter) first in phase and secondly out of phase and the radiation patterns found. Three dimensional plots of the power patterns for these two cases are shown in Figures 1 and 2. The data in Figure 2 is also presented in two different contour forms in Figures 3 and 4. The polar angle θ refers to the angle away from the roll axis of the missile and is measured linearly away from the center of the plot in Figures 1 and 2. The angle φ is the azimuthal angle about the roll axis.

Once the three-dimensional pattern is calculated, the directivity is found numerically and the percent spherical coverage is calculated by the computer. The percent coverage for the two examples of Figures 1 and 2 and for several other combinations are tabulated in Table I.

An attempt was made to use the same numerical techniques described in the previous paragraphs to analyze the LMSC data. It was hoped that the vehicle's scattering and depolarizing effects could be accounted for by using as an element pattern the LMSC radiation pattern for single antenna located on the vehicle. This same pattern could then be assigned to a number of different elements and the effect of phasing these elements could be observed. The extremes (high and low) of the performance of LMSC's two element design was determined by first assuming that the two elements were in phase everywhere (high extreme) in space and then that they were everywhere out of phase (low extreme). The actual Lockheed measured data should then fall somewhere between these two cases. A comparison of the 150 MHz performance numbers with the measured values provided to Georgia Tech at the 14 February meeting are given below.

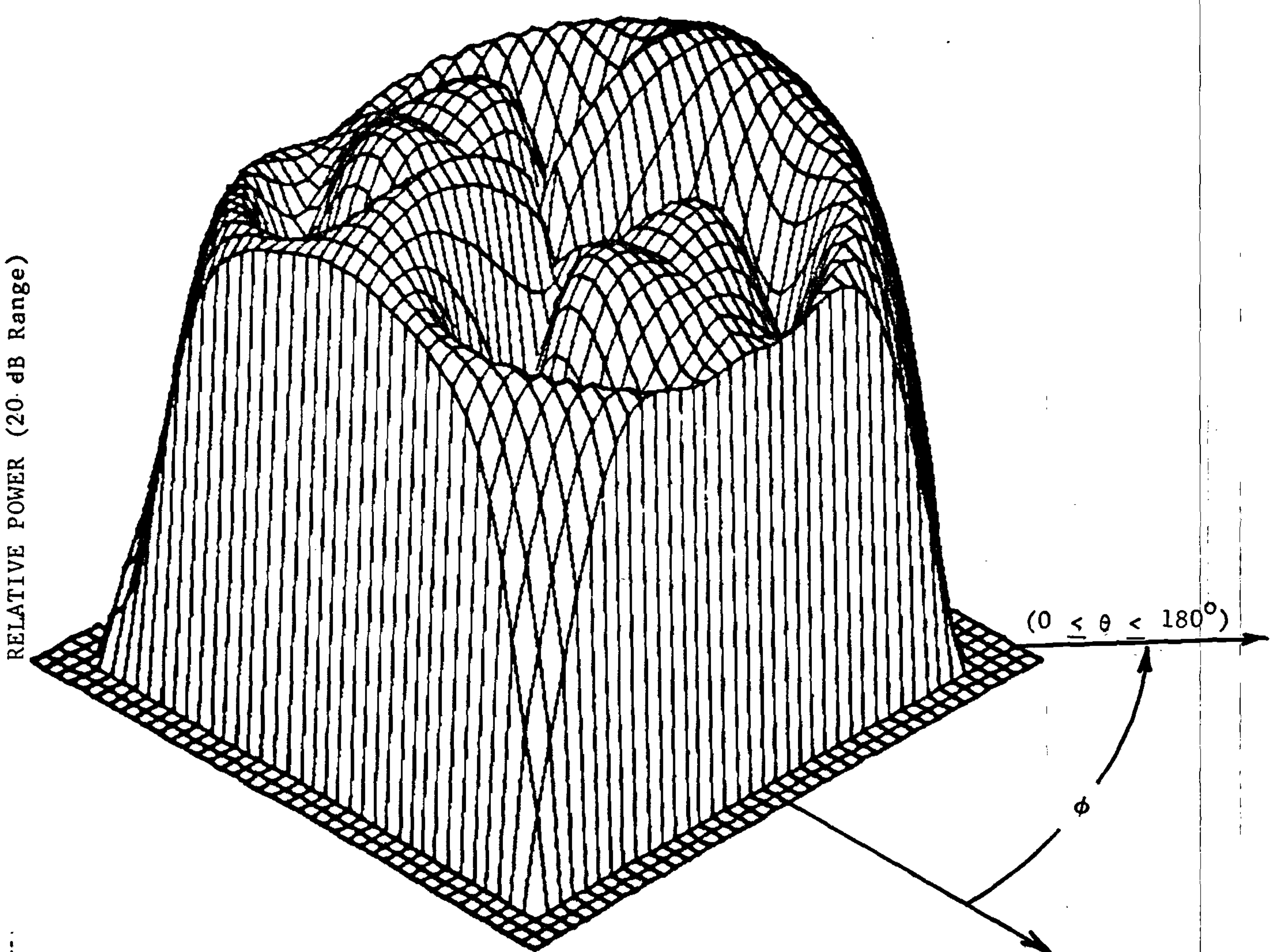

Figure 1. Three dimensional plot of calculated radiation pattern from a two element ring array fed in phase.

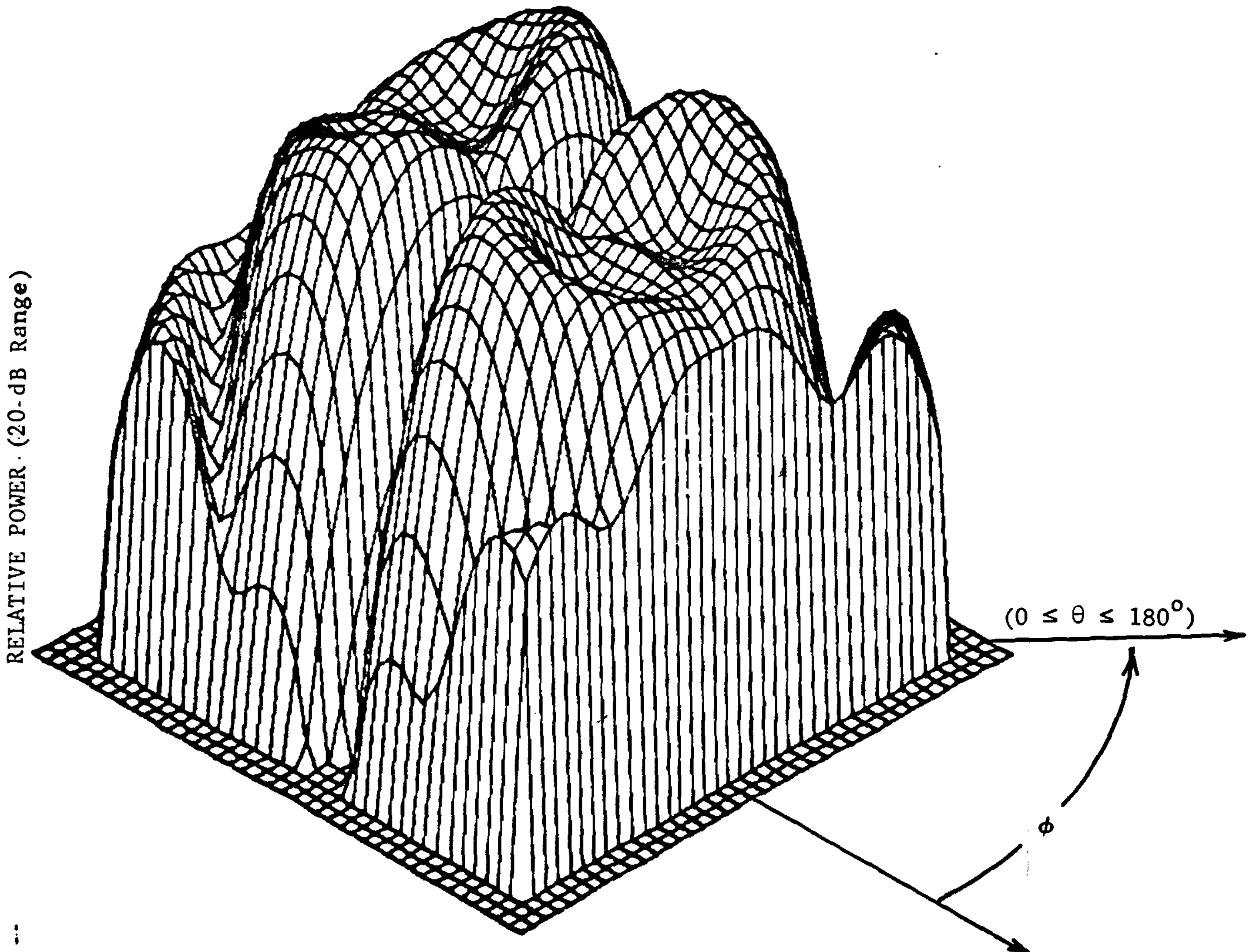

Figure 2. Three dimensional plot of calculated radiation pattern from a two element ring array fed out of phase.

$0^\circ \le \theta \le 180^\circ$ →

φ (Degrees) ↓

```
  0.00   5544443333332222222222222333333444455
  5.00   6554433333333322222222233333333344556
 10.00   6654433222223333333333333222223344566
 15.00   6654432222223333333333333222222344566
 20.00   7654332222222333333333332222222334567
 25.00   8765432211222233333333322221122345678
 30.00   8765432111112222333332222111112345678
 35.00   9875432111111222222222221111112345789
 40.00   $97643211111111111111111111111234679$
 45.00   $$864321110000001111100000011123468$$
 50.00   1$975432110000000000000000011234579$1
 55.00   31$864321100000000000000000112 3468$13
 60.00   4319754321100000000000000011234579134
 65.00   542$86543221100000000000112234568$245
 70.00   7642$875443222111111111222344578$2467
 75.00   +9642$98765443333333333344567 89$2469+
 80.00   32+75421$9877666655566667789$12457+23
 85.00   9863198765433221111111223345678913689
 90.00   *************************************
 95.00   9863198765433221111111223345678913689
100.00   32+75421$9877666655566667789$12457+23
105.00   +9642$98765443333333333344567 89$2469+
110.00   7642$875443222111111111222344578$2467
115.00   542$86543221100000000000112234568$245
120.00   4319754321100000000000000011234579134
125.00   31$864321100000000000000000112 3468$13
130.00   1$975432110000000000000000011234579$1
135.00   $$864321110000001111100000011123468$$
140.00   $97643211111111111111111111111234679$
145.00   9875432111111222222222221111112345789
150.00   8765432111112222333332222111112345678
155.00   8765432211222233333333322221122345678
160.00   7654332222222333333333332222222334567
165.00   6654432222223333333333333222222344566
170.00   6654433222223333333333333222223344566
175.00   6554433333333322222222233333333344556
180.00   5544443333332222222222222333333444455
185.00   6554433333333322222222233333333344556
190.00   6654433222223333333333333222223344566
195.00   6654432222223333333333333222222344566
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210.00   8765432111112222333332222111112345678
215.00   9875432111111222222222221111112345789
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255.00   +9642$98765443333333333344567 89$2469+
260.00   32+75421$9877666655566667789$12457+23
265.00   9863198765433221111111223345678913689
270.00   *************************************
275.00   9863198765433221111111223345678913689
280.00   32+75421$9877666655566667789$12457+23
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300.00   4319754321100000000000000011234579134
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325.00   9875432111111222222222221111112345789
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335.00   8765432211222233333333322221122345678
340.00   7654332222222333333333332222222334567
345.00   6654432222223333333333333222222344566
350.00   6654433222223333333333333222223344566
355.00   6554433333333322222222233333333344556
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* < -40 DB
\# = -30 DB
\+ = -20 DB
$ = -10 DB

Figure 3. Rectangular contour plot of the radiation pattern shown in Figure 2.

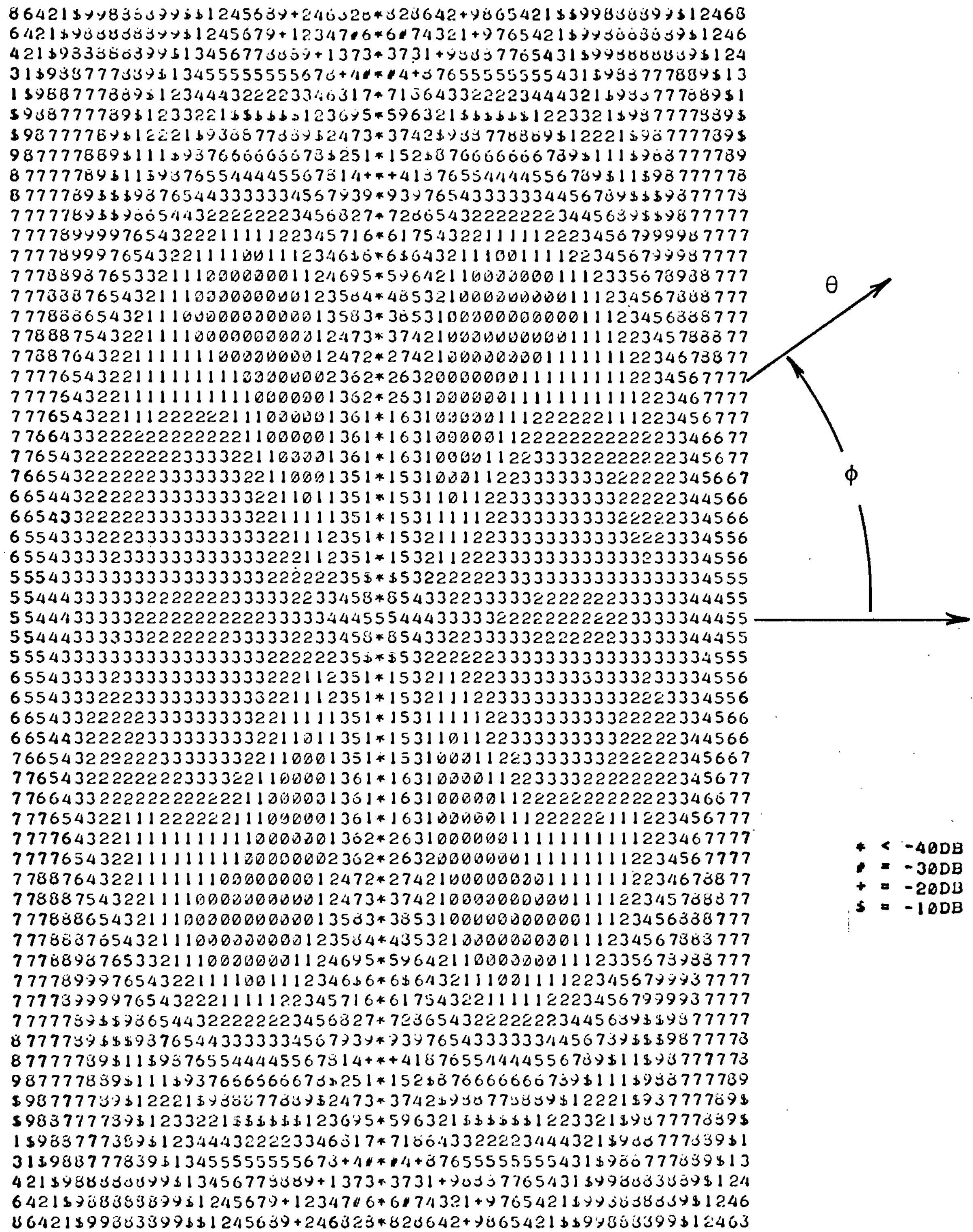


Figure 4. Polar contour plot of the radiation pattern shown in Figure 2.

TABLE I

CALCULATED PERCENT GAIN* COVERAGES FOR A 150 MHz RING ARRAY HAVING THE INDICATED NUMBER AND PHASING OF UNIFORMLY-SPACED ELEMENTS

Number of Elements	Phase Sequence (°)	Directivity** (dB w.r.t. Iso)	50%	90%	95%
1	0	3.5	-2.9	-16.5	-22.5
2	0, 0	3.7	-3.3	- 7.8	- 9.0
2	0, 180	2.9	-2.6	-10.6	-15.6
4	0, 0, 0, 0	4.6	-3.6	- 9.6	-10.8
4	0, 180, 0, 180	4.3	-4.6	-17.0	-21.3
4	0, 0, 180, 180	5.17	-5.3	-16.8	-23.9
4	0, 90, 180, 270	3.6	-3.6	- 9.7	-11.2

*Gain w.r.t a circularly-polarized isotropic radiator

**Directivity for its own particular linear polarization

Antenna	50%	95%
LMSC Measurements on Two Element Array	-10.5	-24.0
Two Elements (In Phase)	- 2.8	- 6.5
Two Elements (Out of Phase)	- 2.9	-11.4

The fact that the measured numbers fall so far below the expected minimum coupled with the fact that the peak value of the LMSC pattern is only -4 dBi indicates that the elements have a poor efficiency. Measured radiation patterns for the two element array were requested from LMSC so that Georgia Tech could numerically calculate the pattern directivity, compare it with the measured gain, and consequently derive the element efficiency. This data finally arrived in April and some time will be spent analyzing it on the computer.

It was suggested by APL personnel during the 19 March meeting that Georgia Tech direct proportionately more time to the development of thin wrap-around antennas than to a numerical analysis of Lockheed's data. Since that time, Mr. J. W. Cofer has been in contact with Mr. Robert Munson of the Ball Bros. Research Corporation concerning the design of microstrip and stripline antennas; however, current designs for this application would require 18 to 20 inches of axial length along the missile. A length of this magnitude is simply not available on the vehicle; consequently, Georgia Tech personnel are looking for techniques to reactively load the elements and thereby shorten the required length without sacrificing efficiency. It is anticipated that Tech personnel will postulate one or more shortening schemes and possibly breadboard at least one of these.

During the forthcoming report period, investigations into the design of electrically small microstrip antennas will continue. The numerical analysis of LMSC data will also continue in an effort to calculate the directivity and consequently the efficiency of this design.

Respectfully submitted,

James W. Cofer, Jr.
SATRACK Project Director

Approved:

D. G. Bodnar, Manager
Electromagnetics Program Office

cc: Addressee
R. B. Hester

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

14 June 1974

Applied Physics Laboratory
Johns Hopkins University
Silver Spring, Maryland

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task II
(SATRACK Study)

Subject: Monthly Contract Technical Status Report No. 2
covering the period 15 April through 31 May 1974.

Dear Dr. Kilgus:

This is the second monthly progress summary under the referenced contract and covers the period 15 April through 31 May 1974.

During this report period, major efforts were directed toward assembling an instrumentation set-up suitable for performing broadband VSWR measurements and testing a few prototype elements. The instrumentation currently being used is depicted in block diagram form in Figure 1. This set-up allows one to view the reflected power as a function of frequency across the band 50-500 MHz. The different points at which the structure under investigation resonates may be observed along with the effects of trimming, shorting, and otherwise altering the element. The X-Y recorder yields documented copies of any interesting data portrayed on the scope by transferring the signal to the recorder and manually sweeping the generator.

The antenna elements which are currently being investigated both theoretically and experimentally are the microstrip patch radiators (see Figure 2) similar to the ones discussed by Munson* of Ball Bros. The first element was a thin sheet of copper foil 92.7 cm(L) by 30.5 cm(W) bonded to the dielectric (fiberglass) of a 3 ft. by 4 ft. sheet of 1/16-inch thick printed circuit board. The element was fed from behind the ground plane as shown in Figure 2 and the output was not shorted. The structure was found to resonate at the following six frequencies:

*R. E. Munson, "Conformal Microstrip Antennas and Microstrip Phased Arrays", IEEE Transactions on Antennas and Propagation, Vol. AP-22, Number 1, Jan. 1974, pp.74-78

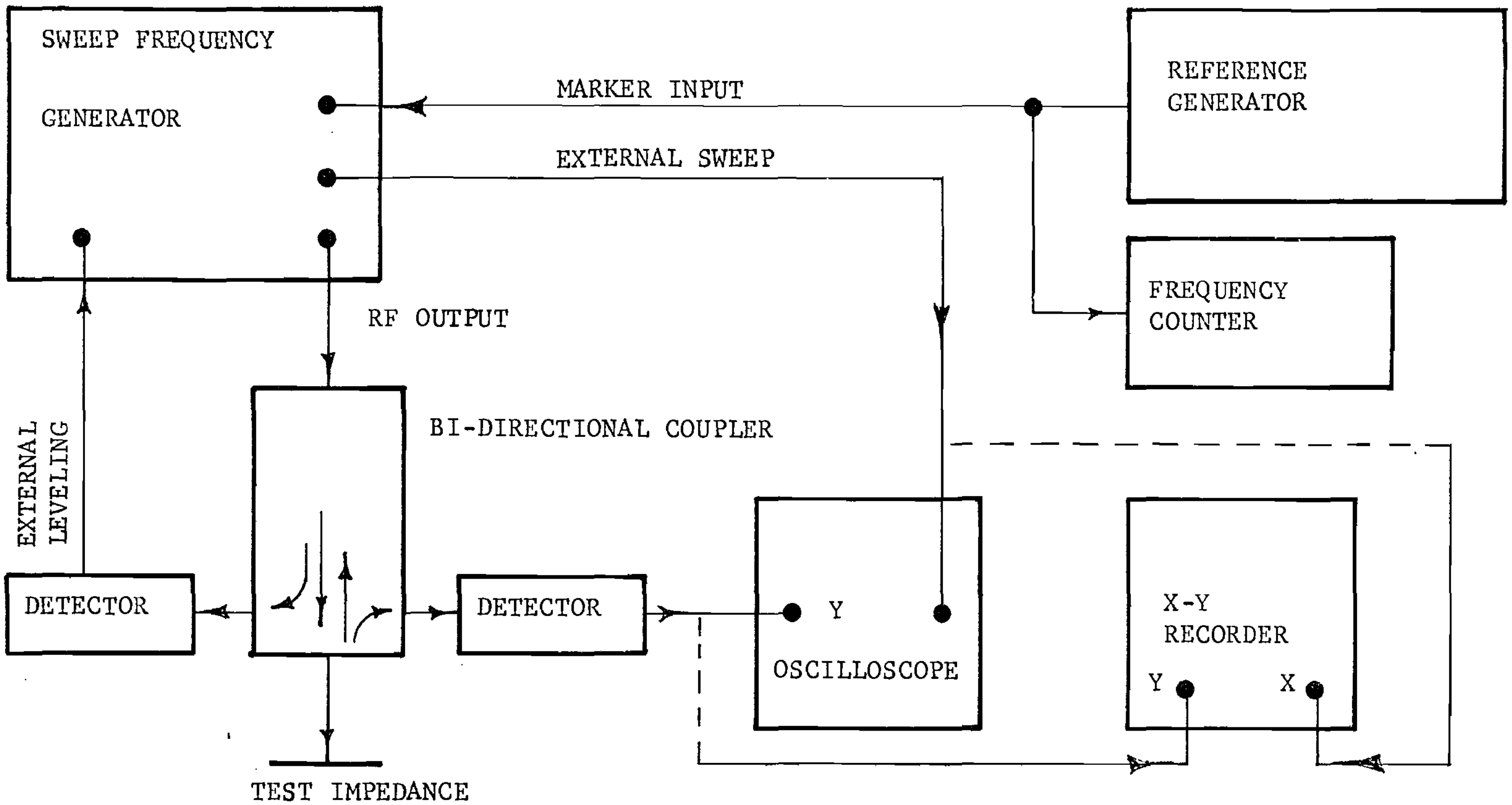
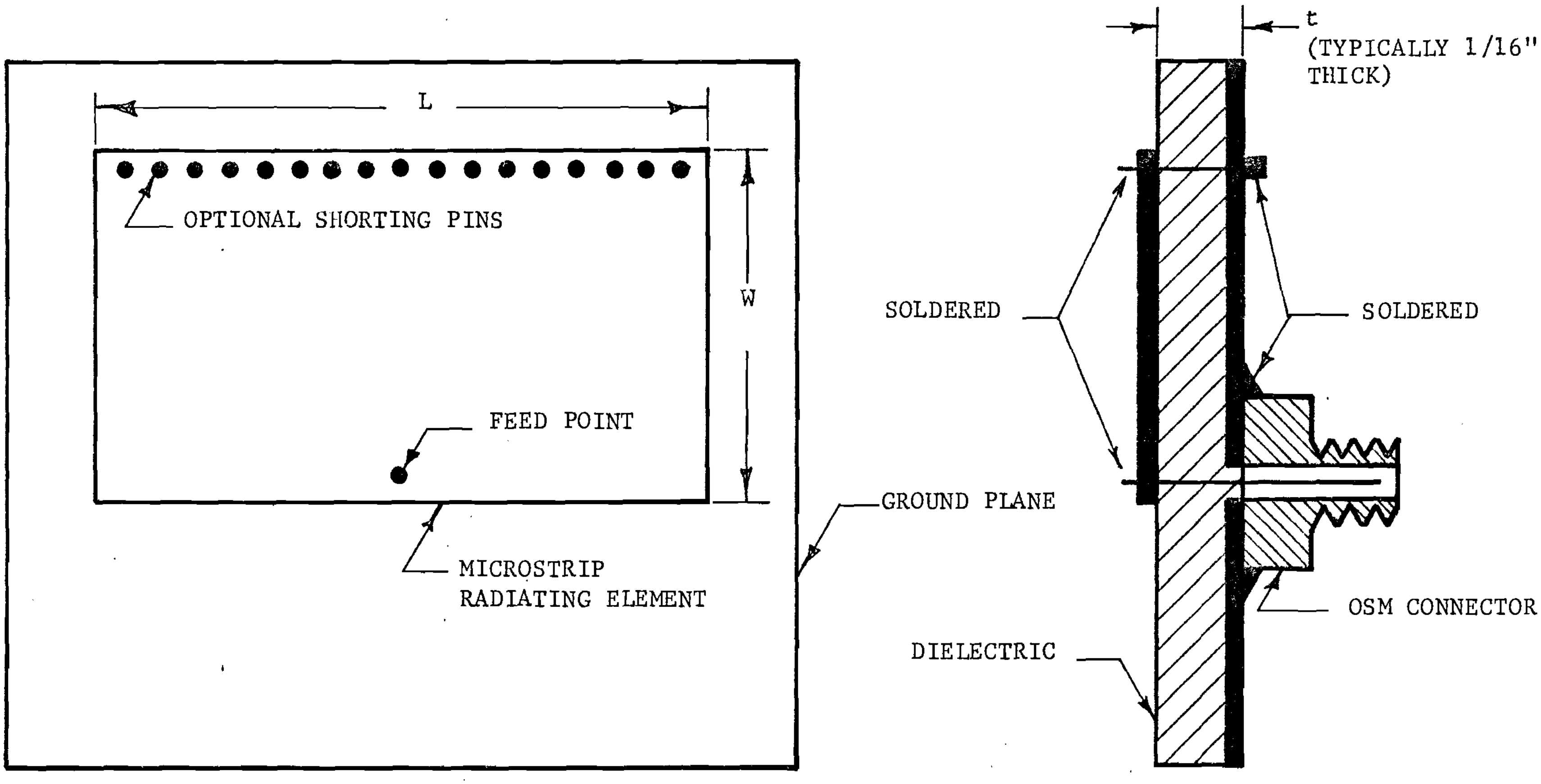


Figure 1. Schematic diagram of instrumentation used to perform and document broadband swept-frequency VSWR measurements.



(a) TOP VIEW (b) SIDE VIEW

Figure 2. Diagram of rear-fed microstrip antenna.

(1) 160 MHz
(2) 240 MHz
(3) 290 MHz
(4) 319 MHz
(5) 403 MHz
(6) 481 MHz

when fed at the point shown in Figure 2. Although a definite resonance could be detected at these frequencies, the element appeared highly inefficient (VSWR between 5:1 and 10:1).

With the length (L) held constant at 92.7 cm, the width (W) was gradually trimmed in one cm increments from 30.5 cm down to about 14 cm. Frequencies (1), (4), and (6) above were virtually unchanged whereas frequencies (2), (3), and (5) varied inversely as the width (W). Specifically, the lowest frequency mode which depended on the width (i.e. frequency (2) above) always had a free-space quarter wavelength or more likely a dielectric half-wavelength equal to the width (W).

With the width held at 14 cm, the length (L) was incrementally shortened and the resonance frequencies observed. As one might expect, the antenna behaved like a dipole in this direction with resonances occurring at frequencies for which the antenna length was 0.5, 1.0, and 1.5 free-space wavelengths. The modes corresponding to these three lengths were the same ones which were unaffected by changes in width, namely (1), (4), and (6) above. VSWR's were still unacceptably high.

The next element investigated was identical to the previous one except that the long side opposite the feed point was shorted to the ground plane. With the width fixed at 14 cm, the length was trimmed in increments from an initial value of 81 cm down to a value of 38 cm. Modes were present which had free-space half wavelengths corresponding approximately to the length (L) as before, but new phenomena were also observed: (1) the VSWR of all modes decreased significantly (as good as 1.2:1 in some cases) and (2) a strange new mode appeared at 200 MHz and was unaffected by changes in length. However, when the width was successively trimmed from 14 to 13 and then to 12 cm, the frequency of this mode varied inversely as the width. The width (W) was found to correspond approximately to a quarter wavelength in the dielectric for this 200 MHz mode. This is theoretically plausible since the short circuit reflects an open circuit in parallel with the feed point impedance. The discovery of this resonance point was very encouraging since it implies that thin elements can be built at the SATRACK frequencies and in sizes small enough to place on the vehicle if the ground plane size can be reduced. The mode whose wavelength varied directly as the length (L) (approximately one-half wavelength) also exhibited some slight dependence on the width (W); consequently, this cross coupling must be considered when designing for two separate frequencies.

At this point, it was felt that enough was known of the theory of operation of the patch radiator to design an element which would oscillate at two independently-controlled frequencies-- namely, 150 and 400 MHz. One element was then fabricated which consisted of a 10"(W) x 16"(L) patch of copper foil on a 3 ft. by 4 ft. sheet of printed-circuit board. The element which is similar to the one in Figure 2 had the side opposite the feed point shorted to the ground plane with a series of closely-spaced screws. A plot of the VSWR of this element as a function of frequency over the range 50-500 MHz is shown in Figure 3. The element had its lowest VSWR (approximately 1.5:1) at 150 and 400 MHz. Although the element is of a size that is easily carried on the vehicle, the associated ground plane is much too large. Consequently, the ground plane was trimmed away in 4 cm steps until the ground plane was the same size as the element. No noticeable degradation of performance was detected as the ground plane was shortened to the size of the element. The entire antenna structure was then 10" x 16" x 1/16".

The results of these experiments can best be described by tabulations of observed advantages and potential problem areas.

Advantages

(1) The antennas are extremely thin (1/16-inch) and lightweight.

(2) The low VSWR's for such electrically small antennas are encouraging.

(3) The possibility exists for designing one structure which resonates at two independently-controlled frequencies having a common feed point. A low-loss diplexer would be used to combine the two signals onto one line.

Potential Problem Areas

(1) The dielectric material which was immediately available was fiberglass which will tend to be more lossy than others such as teflon. A less lossy dielectric might then have a higher VSWR and smaller bandwidth.

(2) The radiation pattern and polarization properties have not been investigated.

On 25 April 1974, Mr. J. M. Schuchardt of Georgia Tech participated in a SATRACK contractors meeting at the facilities of IEC in Anaheim, California. At this time, Mr. E. E. Westerfield of APL asked that Georgia Tech investigate the possibilities of (1) placing on the vehicle a 1.6 GHz system with A Ball Bros. type microstrip wrap-around antenna and (2) adding the signals from any two elements (say the 150 MHz antennas) after detection instead of before.

In response to the first request, array patterns were calculated for 1, 2, 4, and 8 elements fed in-phase at 1.6 GHz, assuming a cardioid element power pattern given by

$$G(\theta,\Phi) = (1 + \sin\theta)\ \left[1 + \cos(\Phi - \Phi_i)\right]$$

Φ_i = location of the ith element,

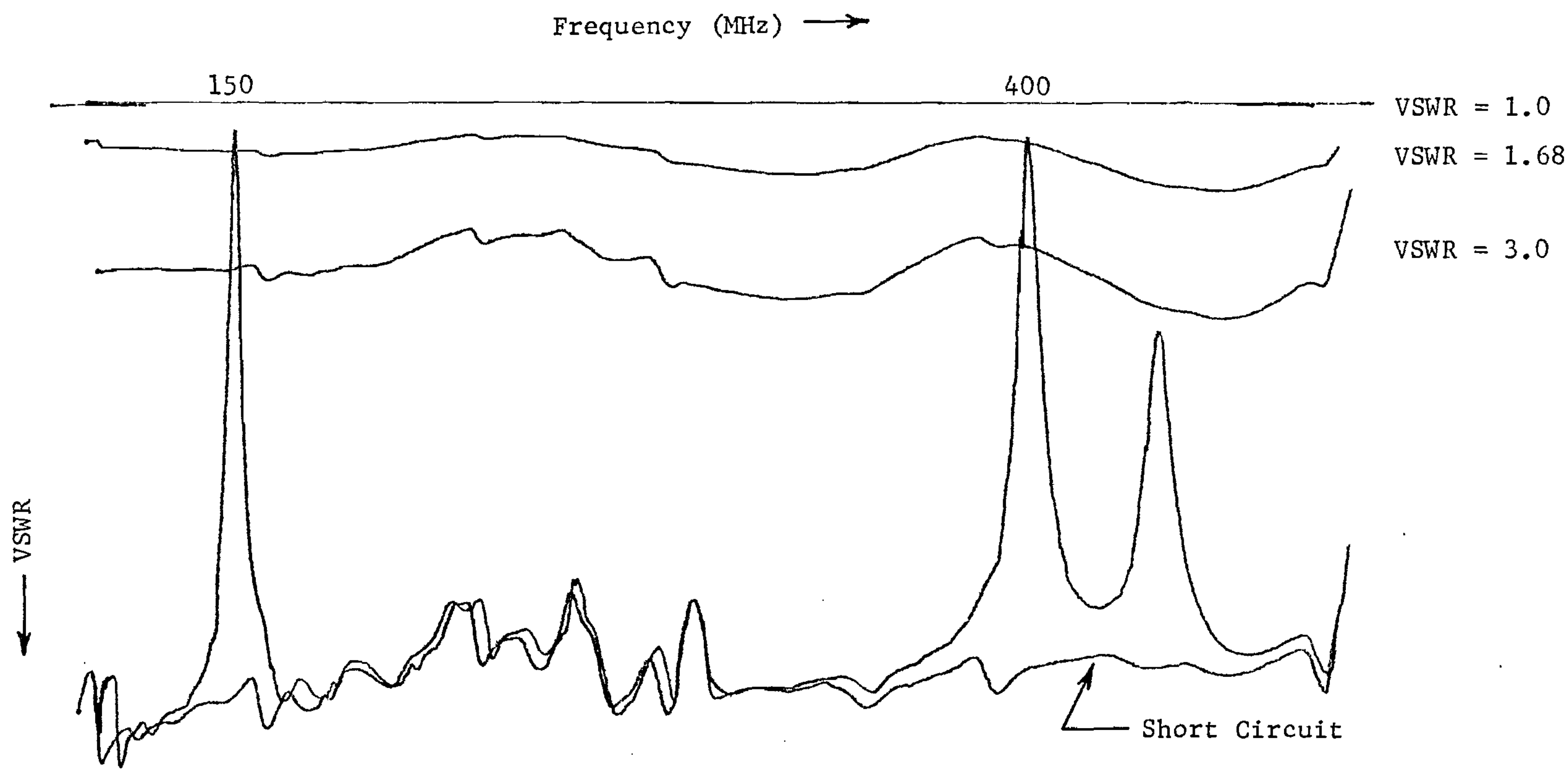


Figure 3. VSWR as a function of frequency for the patch radiator shown in Figure 2. Element is 10 inches by 16 inches and is positioned on a 3 ft. by 4 ft. sheet of 1/16-inch thick fiberglass coated PC board.

and the statistics (dB w.r.t. isotropic) are given below.

Configuration	50%	90%	95%	Directivity
1 element	-0.3	-12.8	-18.5	3.5
2 elements	0.0	- 5.5	- 8.5	3.5
4 elements	-1.9	- 9.9	-15.2	5.6
8 elements	-1.7	-10.2	-12.7	7.3

The numbers in the table above indicate percent coverage over a full sphere, but are referenced to the peak of the beam. In order to give the numbers an absolute level, depolarization and efficiency losses must be substracted. If a polarization loss (circular transmitter and linear receiver) of 3 dB and an efficiency loss of 3 dB (50%) are assumed the above table may be rewritten as follows:

Configuration	50%	90%	95%
1 element	-6.3	-18.8	-24.5
2 elements	-6.0	-11.5	-14.5
4 elements	-7.9	-15.9	-21.2
8 elements	-7.7	-16.2	-18.7

The above numbers indicate that even if the elements were 50% efficient the performance would probably be unsatisfactory for all except the two element array. Also, the three dimensional pattern plots for this frequency are extremely "lobey" with many nulls. Both of these consequencies are due to the fact that the vehicle diameter is so large with respect to a wavelength at 1.6 GHz. According to Munson's criteria, the array would need to be fed at 64 points around the periphery of the vehicle in order to achieve omnidirectional coverage. For the reasons stated above, it is felt that a frequency of 1.6 GHz is impractical for use on a vehicle of this diameter if the signals are to be added at rf. It is felt that performance would be greatly improved at this frequency if the array signals could be added after detection; consequently, this situation will be investigated numerically.

Mr. Westerfield's second question concerning the possibility of adding array signals at dc instead of rf was also addressed. Although more elaborate instrumentation would be required to implement this scheme for the SATRACK program, one can safely say that performance is greatly enhanced over the rf addition method and that it will improve with increasing element numbers since no nulls are ever formed from the addition of out-of-phase signals. An example of such a calculation was given in the 25 April 1974 monthly Technical Status Report. The numbers for this example which compare the dc addition, at every point in space, of a measured LMSC element pattern and the same pattern shifted in azimuth by 180^{o} with the LMSC measured two-element array are repeated below.

Antenna (150 MHz)	50% Level (dBi)	95% Level (dBi)
LMSC measurements on two element array	-10.5	-24.0
DC addition of two element array	- 2.8	- 6.5

The above calculated data includes a polarization loss of 3 dB but assumes 100% efficiency.

As stated in last month's progress report, the contour plot of the LMSC two-element 150 MHz array was received in April. The radiation levels on this pattern plot were analyzed on the computer to determine the peak directivity and statistical gain levels. A three-dimensional computer plot of this data is shown in Figure 4. These gain levels, with the peak normalized to the gain indicated by Lockheed, are listed below in dB with respect to a circularly polarized isotropic radiator.

GAIN LEVELS OF THE LMSC 150 MHz TWO ELEMENT ARRAY

Peak Value (0%)	50%	80%	90%	95%	Calculated Directivity
-4.0	-9.2	-14.0	-17.2	-20.7	5.1

Note that the difference between the calculated directivity and reported gain is 9 dB. If 3 dB of this can be attributed to polarization loss, then the other 6 dB must correspond to efficiency and cable losses.

On 14 May 1974, Dr. D. G. Bodnar of Georgia Tech accompanied Dr. C. C. Kilgus of APL in a visit to LMSC facilities in Sunnyvale, California. At this time Lockheed personnel displayed data for a new 150 MHz antenna design which is superior in performance to the previous design presented in February. The new antenna consists of an array of four tri-plate vanes each over a ten by fifteen inch ground plane. Over 90% of the sphere, the gain of this array is greater than -14.1 dB. Although this coverage is approximately 1 dB out of spec, it is significantly better than the previous design and is considered acceptable. It must be noted, however, that two aspects of the procedure by which this data was derived are open to question and must be clarified in the final tests--(1) the measurements were made relatively close to the ground on an outdoor range and, therefore, are subject to reflection errors and (2) the absolute gain assigned to the peak of the pattern was not actually measured but rather is the result of calculating a directivity from measured data and subtracting assumed efficiency, polarization, and cable losses from it.

During this visit, Dr. Bodnar was able to obtain a contour plot and the associated punched paper tape of the radiation pattern from this new 150 MHz array. Firstly, a copy will be made of this tape and forwarded to APL, and secondly, the data will be analyzed on existing Georgia Tech computer programs to verify the LMSC directivity and coverage levels.

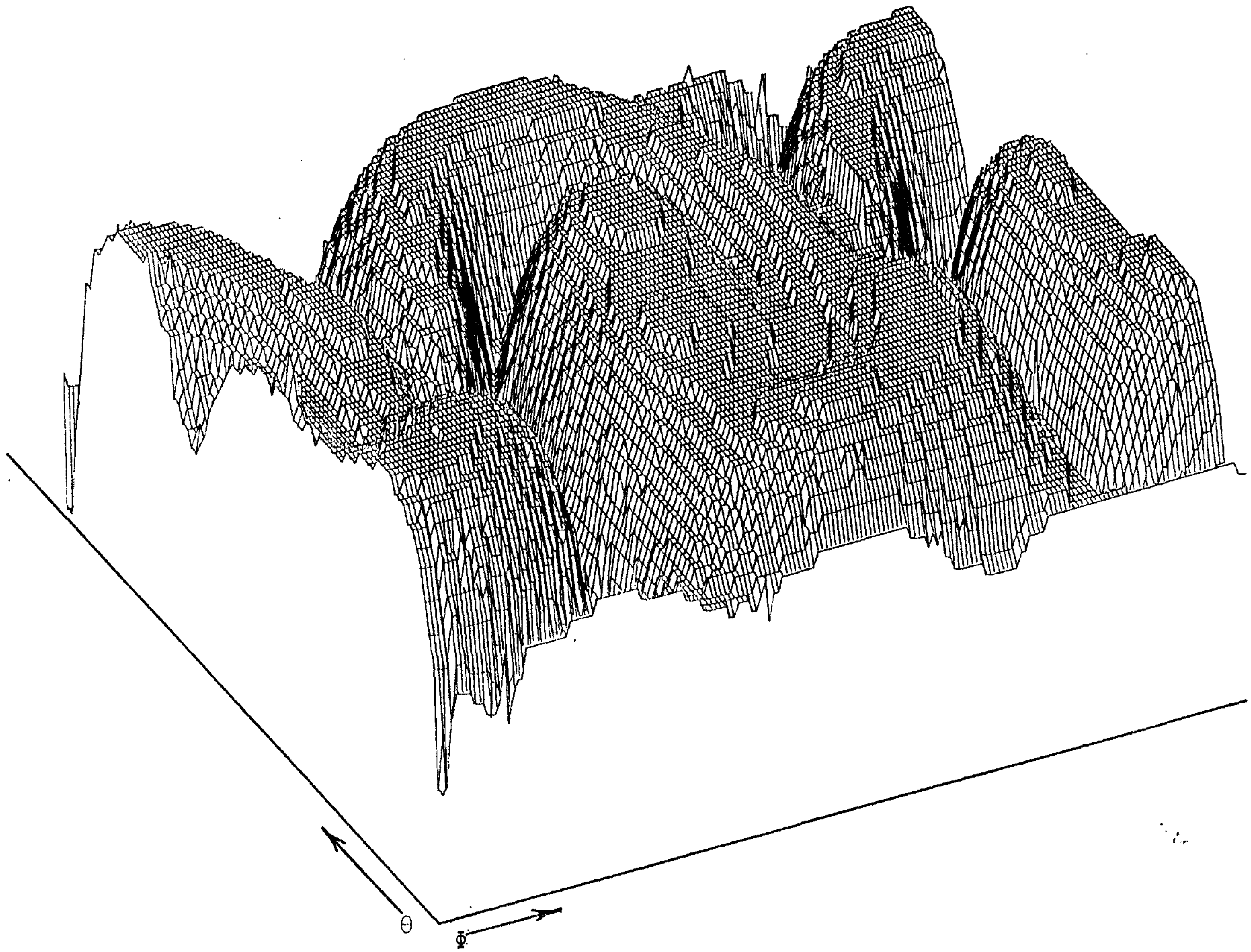


Figure 4. Three-dimensional rectangular plot of the 150 MHz two element array measured by LMSC.

The results of this analysis will be given to APL in June in the form of a Special Technical Report.

Dr. Bodnar learned during this trip that LMSC plans to use a two element array at 400 MHz. The computer programs described in the first Status Report will be used during the period 1 June to 30 June to determine the number and phasing of elements deemed necessary at 400 MHz.

During the forthcoming report period, the testing of microstrip antennas will continue. Emphasis will be placed on the polarization and radiation characteristics of the current dual frequency structure. As stated above, the investigation of the antenna needs at 400 MHz will continue. In particular, a computer program using moment methods has been obtained from Dr. B. J. Strait of Syracuse University in order to take into account the effect of the vehicle's presence on the radiation pattern. It is hoped that this numerical technique will be adapted to our application during June.

Respectfully submitted,

James W. Cofer, Jr.
SATRACK Project Director

JWC:jm

Approved;

D. G. Bodnar, Manager
Electromagnetics Program Office

cc: Addressee

R. B. Hester

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

12 July 1974

Applied Physics Laboratory
John Hopkins University
Silver Spring, Maryland

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task II
(SATRACK Study)

Subject: Monthly Contract Technical Status Report No. 3
covering the period 1 June through 31 June 1974.

Dear Dr. Kilgus:

This is the third monthly progress summary under the referenced contract and covers the period 1 June through 31 June 1974.

Major efforts during the early portion of the month were directed toward an analysis of the data measured by LMSC on their four-element array. The results of this analysis were submitted to APL on 5 June 1974. A brief summary of those results is included herein. This data, measured every 2^o in θ and Φ for $0^o \leq \theta \leq 180^o, 0^o \leq \Phi \leq 360^o$, is presented in three-dimensional rectangular form in Figure 1. A computer analysis of the coverage levels for this data yields the power distribution function shown in Figure 2. Some confusion existed since too much data was present on the tape (i.e., usually more than 180^o in θ and more than 360^o in Φ is present); consequently, two different but overlapping blocks of the data were processed (reading from front and back of tape). Several representative percent coverage levels for these two blocks of processed data are given in Table I along with the corresponding percentages calculated by LMSC. All three analyses yielded similar results which are very close to the specified level (- 13 dBi over 90% of the sphere).

Shortly after these results were submitted to APL, it was learned that the 150 MHz channel would probably be replaced by one operating at the frequency of the Global Positioning System (approximately 1.6 GHz). The particular combination of SATRACK geometry (large diameter vehicle) and GPS frequency are very undesirable especially in view of the fact that phase

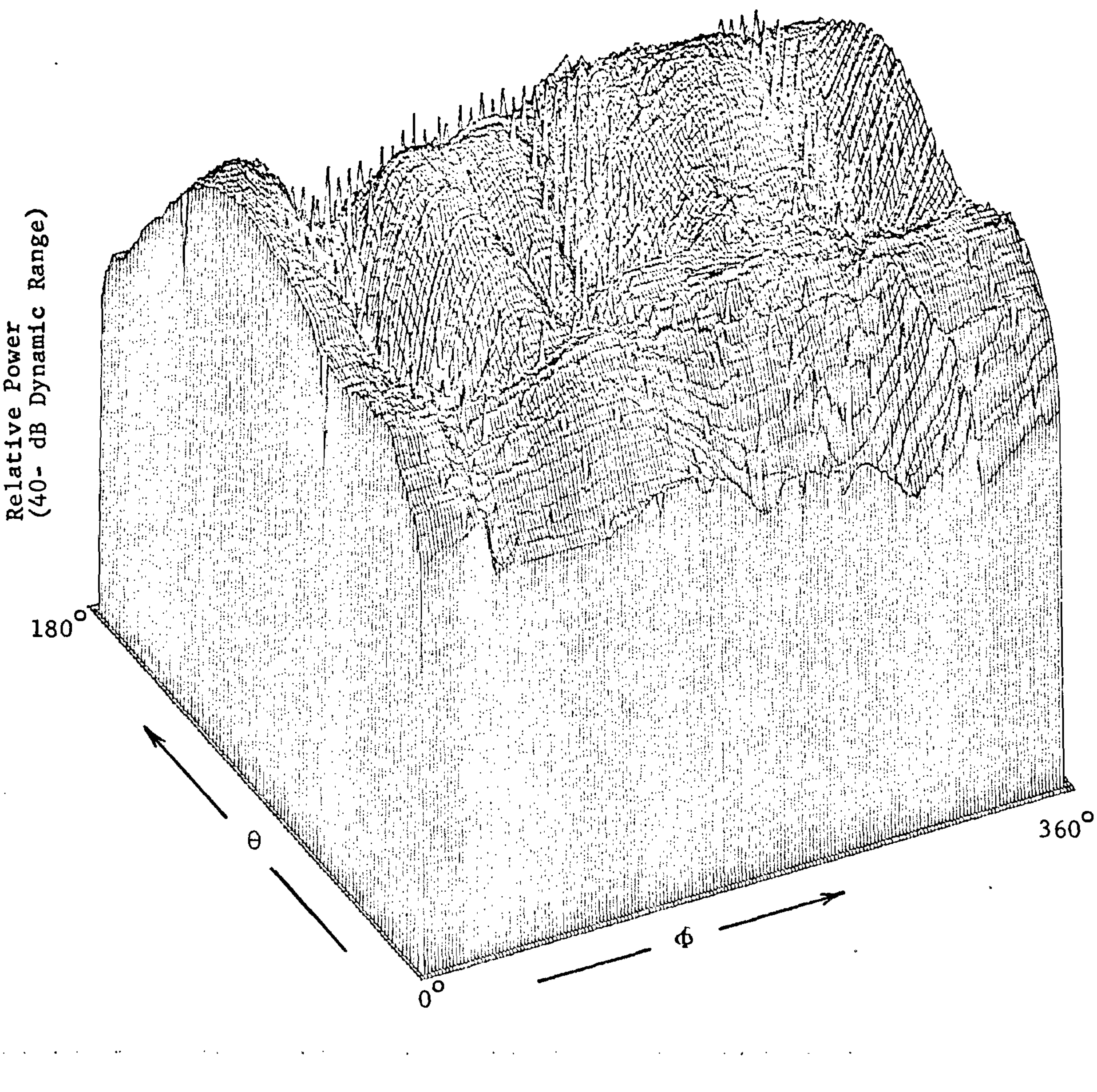


Figure 1. Rectangular three-dimensional plot of the data measured on the 150-MHz 4-element array when reading from the rear of the tape.

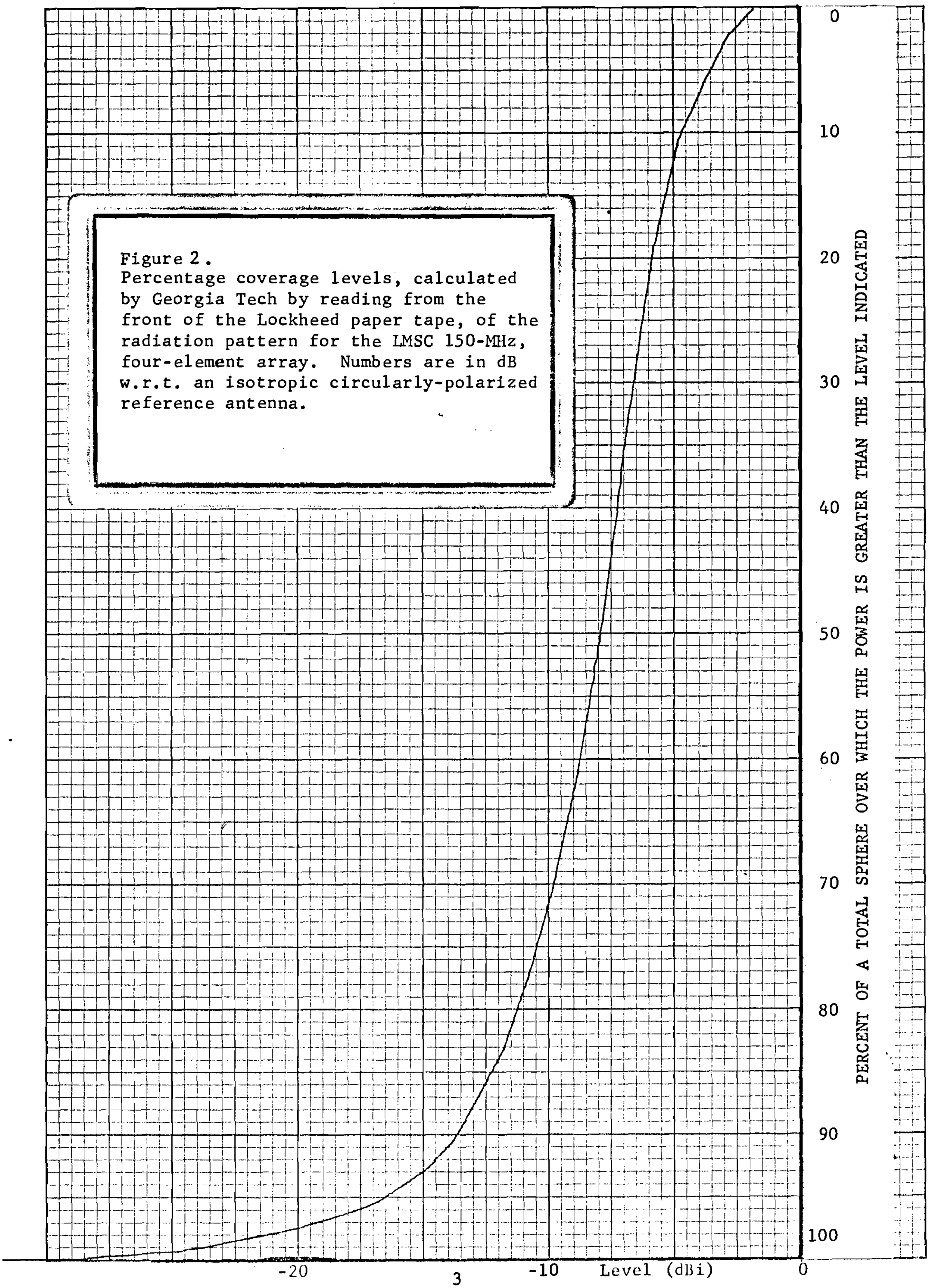


Figure 2.
Percentage coverage levels, calculated by Georgia Tech by reading from the front of the Lockheed paper tape, of the radiation pattern for the LMSC 150-MHz, four-element array. Numbers are in dB w.r.t. an isotropic circularly-polarized reference antenna.

TABLE I

COMPARISON OF SELECTED COVERAGE LEVELS* FOR THE LMSC 150-MHz 4-ELEMENT ARRAY FOR THREE SEPARATE ANALYSES OF THE SAME DATA.

	Directivity	Peak Level	50%	80%	85%	90%	95%
Georgia Tech Analysis I (Reading front of tape)	5.77	-1.73	-7.9	-11.2	-12.3	-13.7	-16.5
Georgia Tech Analysis II (Reading rear of tape)	5.73	-1.77	-7.9	-11.3	-12.3	-13.7	-16.8
Independent Lockheed Analysis	5.64	-1.86	-8.2	-11.6	-12.6	-14.1	-17.1

*Levels are in dB w.r.t. a circularly-polarized isotropic source and include assumed polarization, efficiency, and cable losses.

variations in the radiation pattern will reportedly deteriorate tracking performance.

In order to obtain a better feeling for the number of elements which would be required at this frequency, scalar radiation patterns were calculated for several 72-inch ring arrays having different numbers of elements. Patterns were calculated only in the plane of the array to determine the number required to remove the ripple in the roll plane. The patterns for 2, 4, 8, 16, 32, and 64 elements are shown in Figures 3 through 8, respectively. Apparently, at least thirty-two elements would be required to achieve near-omni coverage and consequently constant phase.

Several element types have been considered for this application and three of the more important ones are listed below:

(1) Ball Brothers Wraparound
(2) Biconical Horn
(3) Array of Discrete Cavity Elements

Using Ball Brothers' criteria, the wraparound would need at least 48 feed points. This large number of feed points and the associated number of stripline transformers coupled with the fact that certain immovable devices on the vehicle prevent the installation of a complete wraparound antenna make this candidate undesirable at this time. However, this antenna would provide the required coverage.

A biconical horn was postulated to APL in a Technical Memorandum because the element is small, broadband, and has excellent coverage for the present application. This scheme, which is depicted in Figure 9, was discussed at length with LMSC, and it was determined that space is not available along the vehicle axis.

The third candidate is the least desirable since it implies either a large number of elements or a small number with their associated interferometer-type pattern. At this point, it is understood that LMSC is considering this approach first due to the simplicity and economy involved. If it is determined that the system actually will not function in the presence of abrupt phase changes, this approach will probably be unsatisfactory since several nulls and phase jumps can be expected from use of only a few elements.

On 5 June 1974, Dr. D. G. Bodnar and Mr. J. W. Cofer of Georgia Tech visited APL facilities to discuss the SATRACK program. At that time, the performance of the LMSC, 4-element, 150-MHz array was discussed. Also, a thin microstrip antenna fabricated by Georgia Tech was presented and discussed.

A system meeting involving APL, LMSC, IEC, the Navy, and Georgia Tech was tentatively planned for 26 June 1974 at Sunnyvale, California to discuss the implications of the change to 1.6 GHz. This meeting was later changed to 2 July 1974 and will be discussed in the July Monthly Status Report.

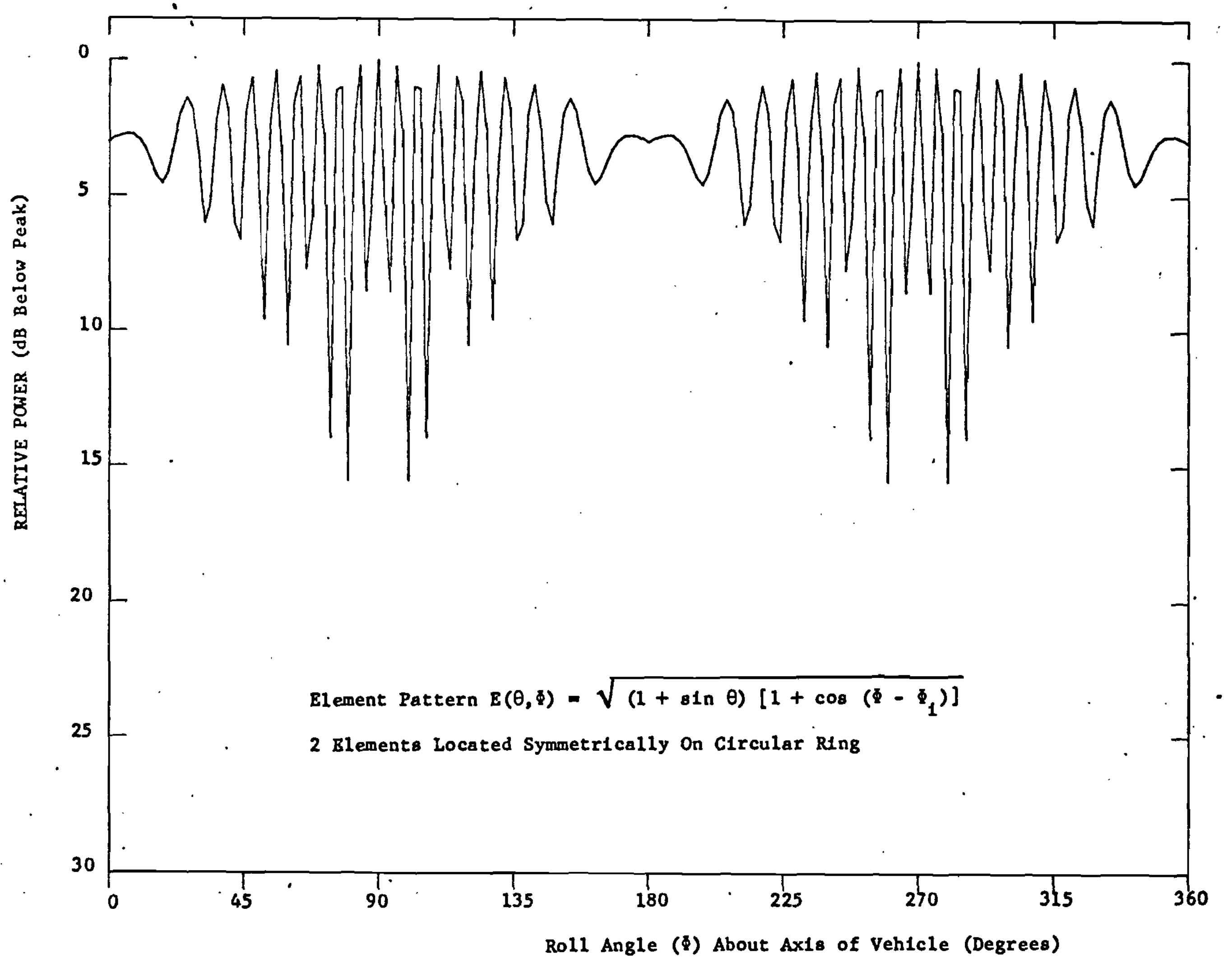


Figure 3. Calculated radiation pattern in the $\theta = 90^{\circ}$ plane from an array of 2 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

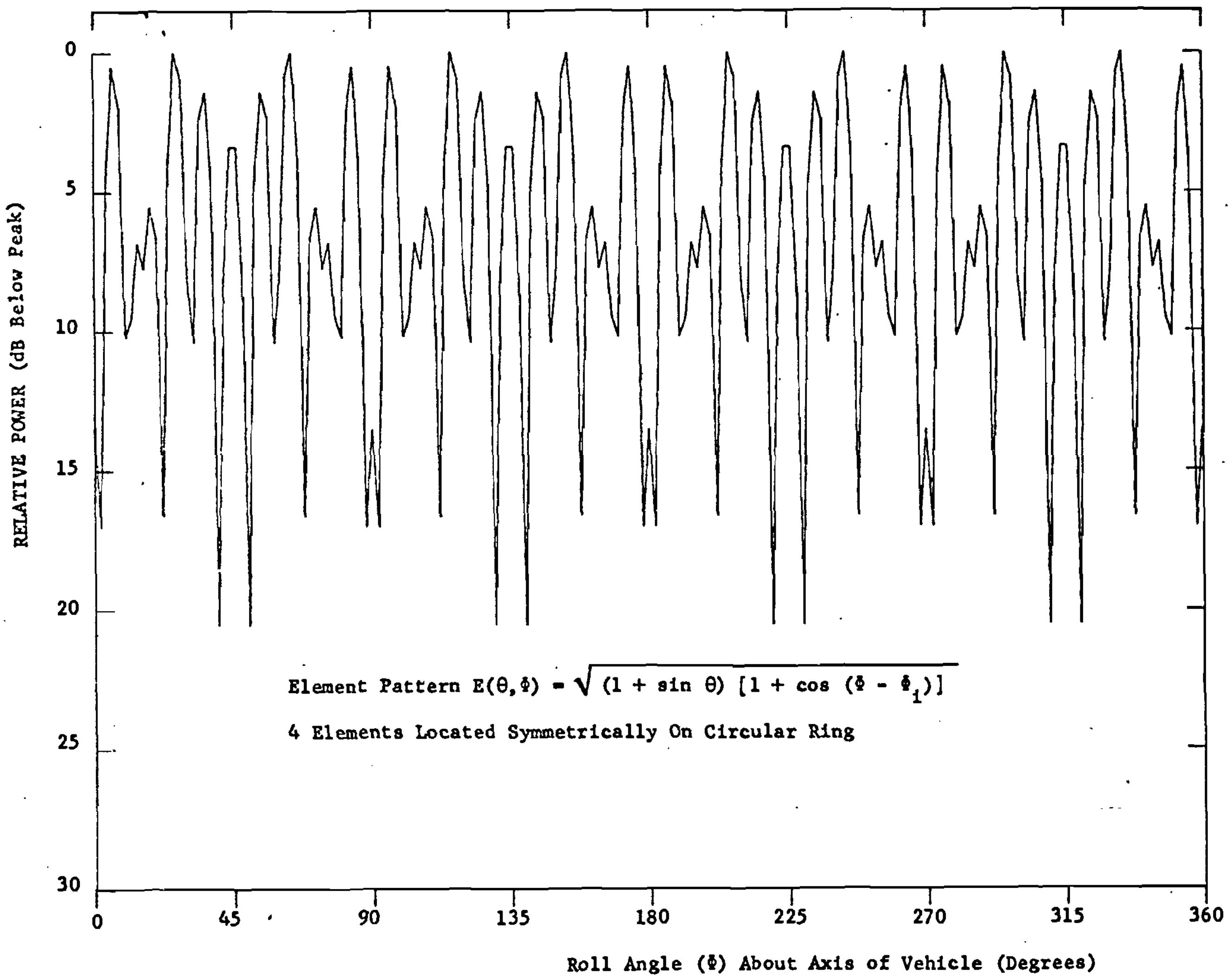


Figure 4. Calculated radiation pattern in the θ 6 90° plane from an array of 4 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

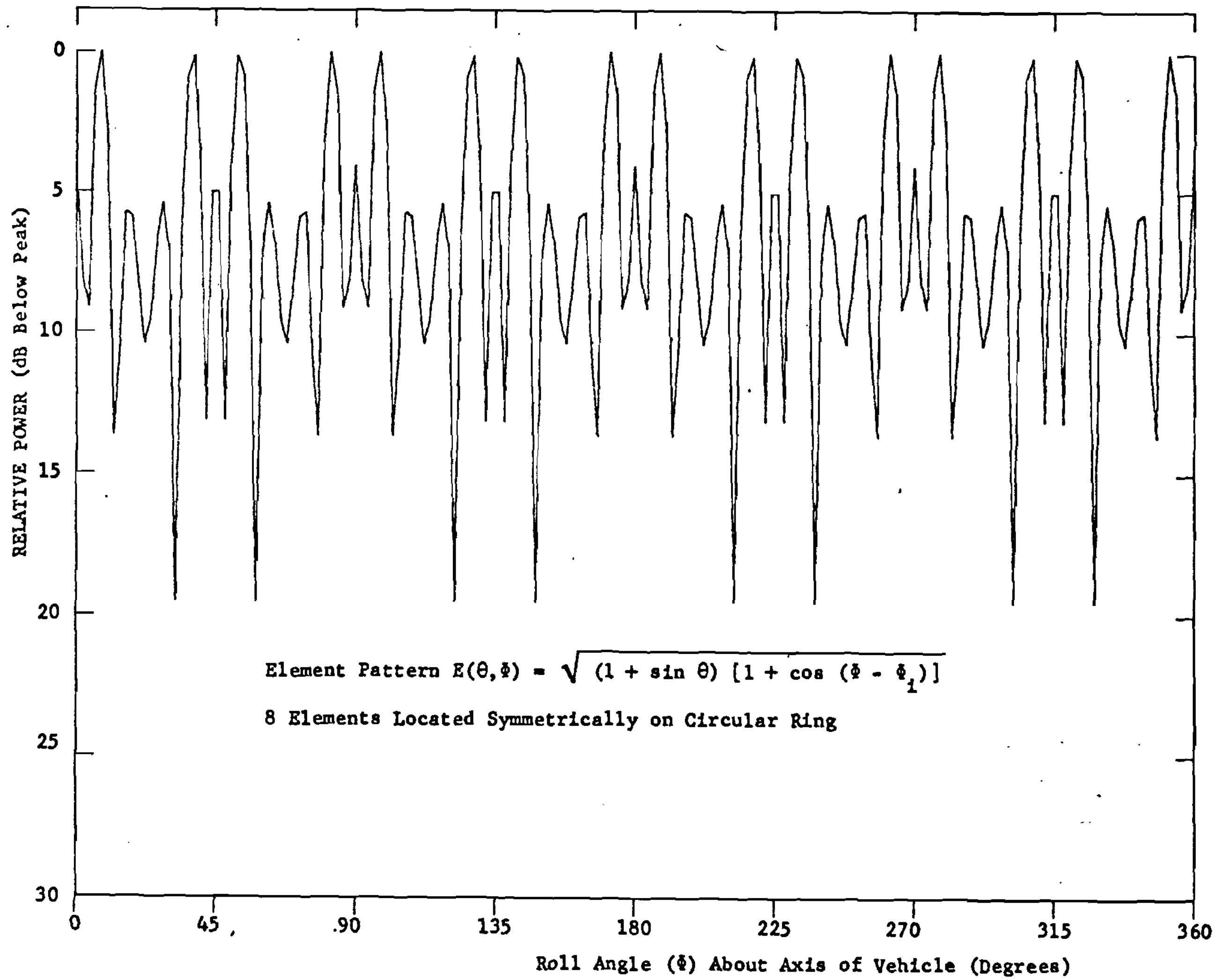


Figure 5. Calculated radiation pattern in the $\theta = 90^\circ$ plane from an array of 8 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

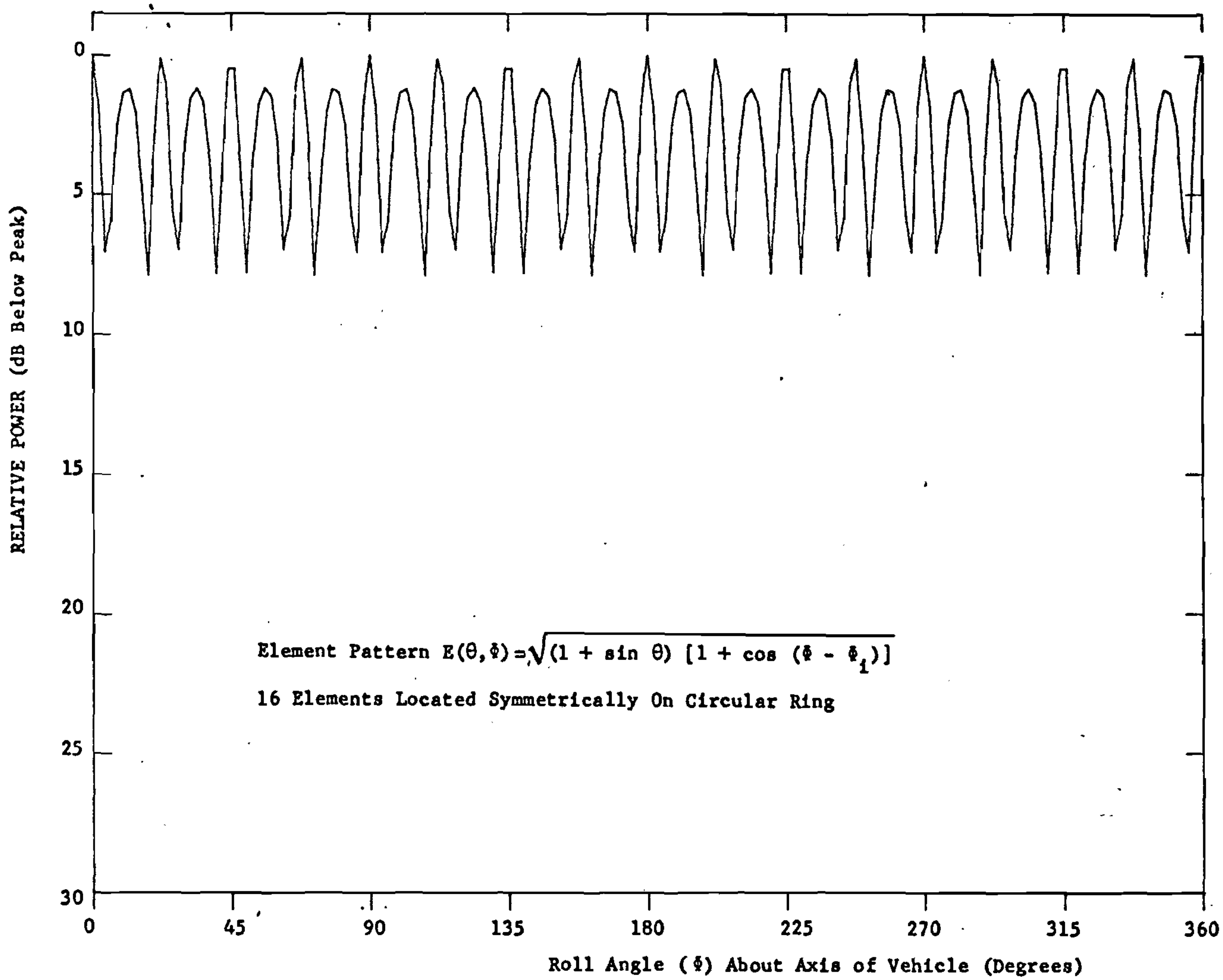


Figure 6. Calculated radiation pattern in the $\theta = 90^{\circ}$ plane from an array of 16 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

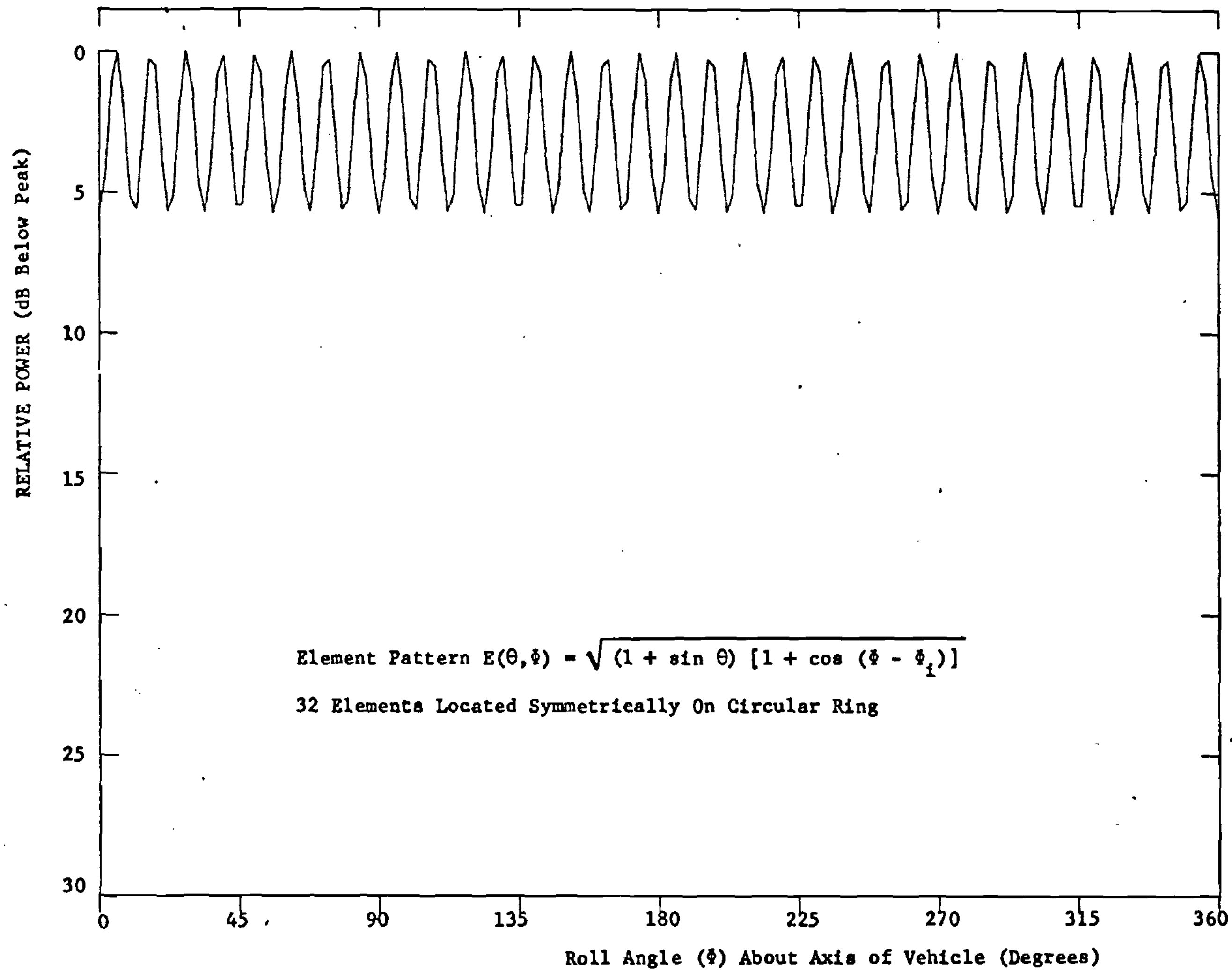


Figure 7. Calculated radiation pattern in the $\theta = 90^{o}$ plane from an array of 32 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

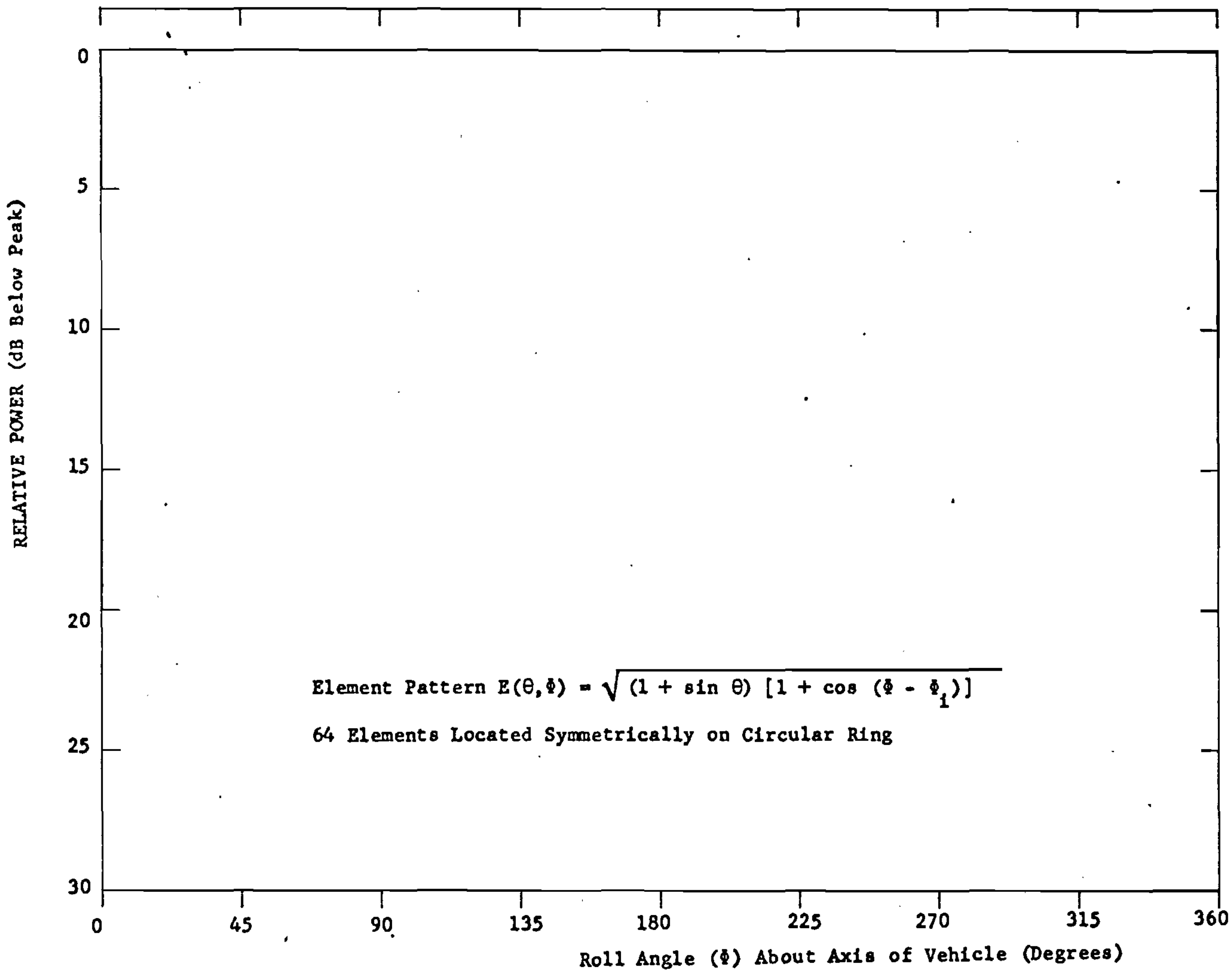


Figure 8. Calculated radiation pattern in the $\theta = 90^{\circ}$ plane from an array of 64 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

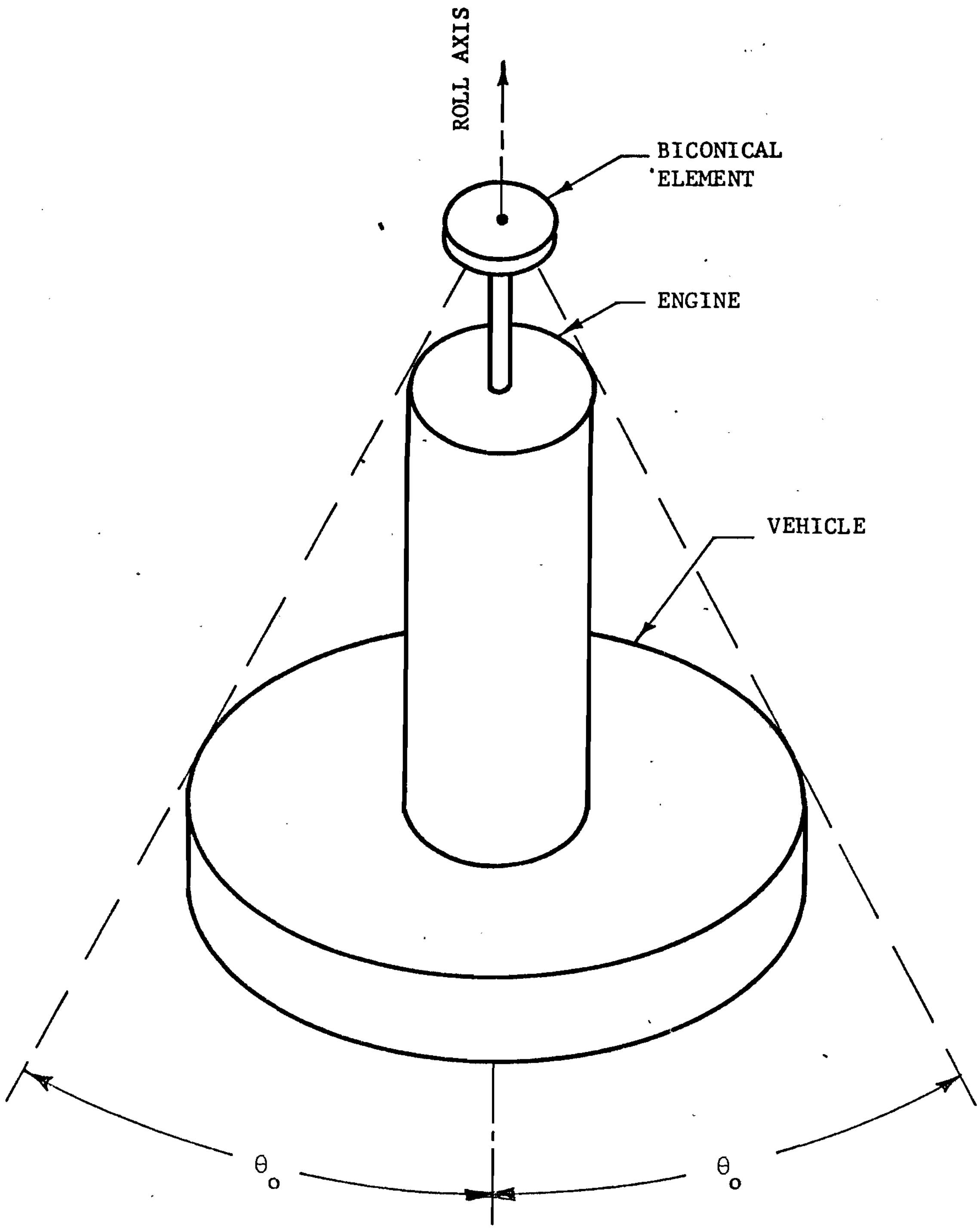


Figure 9. Suggested placement of one biconical element on the SATRACK vehicle.

As of 1 July 1974, $21,100.76 of the total contract funds ($24,957.00) have been expended leaving an unexpended balance of $3,856.24. This figure includes no retirement charges, which should amount to approximately $1,000.00 for the total contract, and does not include travel charges to Sunnyvale, California for Mr. Cofer on 2 July 1974 (approximately $425.00). Consequently, the total free balance remaining is approximately $2,400.00 corresponding to $1,381.00 for personal-service charges. It is felt that these funds are just sufficient for completing the project tasks and submitting the Final Technical Report. It is hoped that the extension to the program which has already been proposed will be negotiated in time to allow Georgia Tech to maintain continuity with the program.

During the forthcoming report period, the moment method analysis of the vehicle at 400 MHz will be completed. Also, the writing of the Final Technical Report will be initiated.

Respectfully submitted,

James W. Cofer, Jr.
SATRACK Project Director

JWC:jm

Approved:

D. G. Bodnar, Manager
Electromagnetics Program Office

File: A-1617-100

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

19 August 1974

Applied Physics Laboratory
Johns Hopkins University
Silver Spring, Maryland

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Ammendment No. 1, Task 2
(SATRACK Study)

Subject: Monthly Contract Technical Status Report No. 4 covering the period 1 July through 31 July 1974

Gentlemen:

This is the fourth Monthly Progress Summary under the referenced contract and covers the period 1 July through 31 July 1974.

During this time period, major efforts were directed toward calculation of the coverage expected at 400 MHz using both scalar and moment method techniques and also a phase analysis of the newly proposed time diversity system. The complete results of these investigations will not be presented here as they will be included in the Final Technical Report which will be published in August 1974. This report will be forwarded to APL immediately after reproduction. A summary of the major results of these investigations, however, is given in the following paragraph.

Calculations at 400 MHz using both the scalar and the moment techniques indicate that a serious design problem is present at this frequency. Both theoretical approaches indicated that a 90% coverage level on the order of about -15 dBi circular is a typical number to be expected. This number is considerably below the specified value. The use of circular polarization or possibly the newly proposed time diversity appears warranted at 400 MHz.

During the latter part of July, it was proposed by APL and/or LMSC personnel that a time diversity scheme be considered. Using this scheme, one pair of diametrically opposite elements would be combined coherently and a second pair of diametrically opposite elements which were located orthogonally in space to the first pair would also be combined coherently to give two separate rf outputs. The input to the translator would be switched very rapidly between these two rf inputs and a receiver on the ground would choose the larger of the two signals; consequently, no nulls would be formed due to rf addition of signals from a four-element array. APL personnel have indicated interest in the type of phase variations which might be expected from a two-element array; therefore, Georgia Tech calculated the far-field phase variation, using the scalar technique, for a two-element array. Initial results indicated that the phase variations were quite severe; however, it was noted that the variations due strictly to the geometric movement of the elements with respect to the center axis of the vehicle produced a very large sinusoidal phase variation. Since the vehicle is not expected to roll rapidly, this geometric variation is not considered critical; however, any instantaneous phase jumps due to nulls in the far-field pattern would be of interest to APL. Consequently, the patterns were calculated again with the geometric terms subtracted out in the region where each element dominated and the resulting phase variations were found to exist only in the region halfway between the two elements where the orthogonal pair would be chosen anyway. These phase variations present were on the order of $\pm 45^{\circ}$ and were in the neighborhood of $\Phi = 90^{\circ}$. Plots of this data will be included in the Final Technical Report.

As of 1 August 1974, $24,423.04 of the total contract funds ($24,957) have been expended leaving an unexpended balance of $533.96. This figure includes all charges which have been encumbered by the project as of 1 August 1974. The remaining funds are just sufficient to complete publication of the Final Report during the month of August. Georgia Tech has subsequently submitted an unsolicited proposal to continue the present work at a cost of approximately $49,972 for a 12-month period beginning 15 August 1974.

Anticipating that this proposal will be funded, Georgia Tech personnel are proceeding with certain tasks which they feel to be vital to the continuity of the SATRACK program. In particular, the coverage to be expected using the time diversity system will be investigated during the month of August. Also, it is hoped that sufficient mock-up dimensions will be obtained during the August trip to LMSC so that Georgia Tech may fabricate a model of the vehicle so that more realistic impedance and pattern measurements may be obtained.

Respectfully submitted,

James W. Cofer, Jr.
SATRACK Project Director
A-1617-100

JWC/mac

Approved:

D. G. Bodnar, Manager
Electromagnetics Program Office

cc: Mr. R. B. Hester

File: A-1617-100

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

16 September 1974

Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Ammendment No. 1, Task 2
(SATRACK Study)

Subject: Monthly Contract Technical Status Report No. 5
covering the period 1 August through 31 August 1974

Gentlemen:

This is the fifth Monthly Progress Summary under the referenced contract and covers the period 1 August through 31 August 1974.

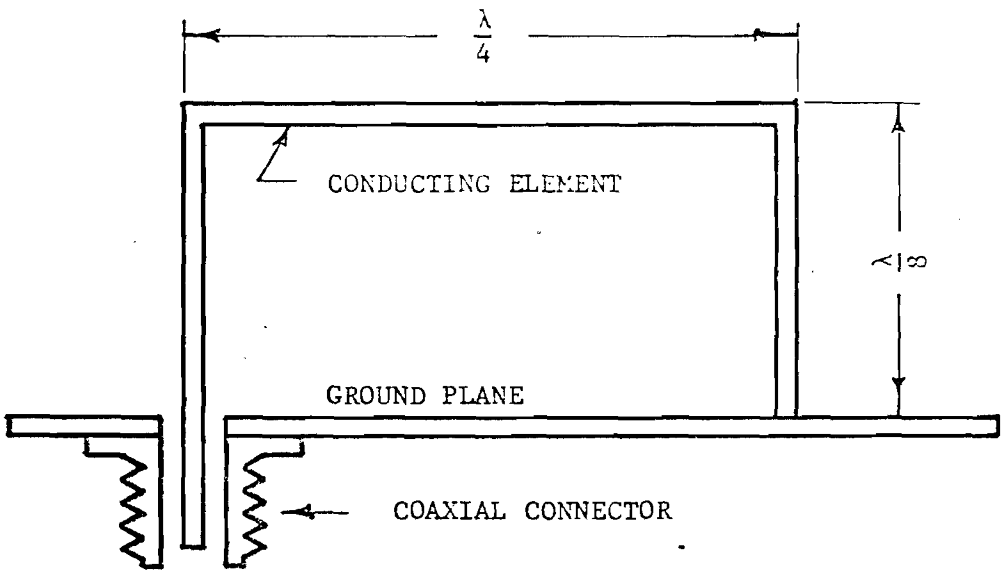
During this report period, the Final Technical Report was completed and submitted. This report covered all aspects of the work performed under the referenced contract from 14 February 1974 to 15 August 1974 and was distributed by the Georgia Tech Research Institute on 21 August 1974. The basic findings documented in that report (not including the now irrelevant 150-MHz studies) were that it will be extremely difficult to achieve broad coverage without numerous nulls at both 400 MHz and 1600 MHz unless a very large number of elements is used. It was recommended that circular polarization be used for elements at both frequencies and that time diversity be considered for use at 400 MHz as well as 1600 MHz.

On 14 August 1974, Dr. D. G. Bodnar and Mr. J. W. Cofer of Georgia Tech met with Dr. C. C. Kilgus of APL in San Francisco to discuss the future of the SATRACK effort at Georgia Tech and also some of the elements recommended by Tech personnel. The following day, 15 August 1974, Drs. Bodnar and Kilgus and Mr. Cofer met with Mr. Frank Butscher of LMSC at the Lockheed facilities in Sunnyvale, California. Mr. Butscher stated that a particular element had not been chosen yet for either frequency although several candidates were being considered,and that the final element choice would be made based on the outcome of a series of anechoic chamber measurements beginning on 19 August 1974. At that time, Dr. Kilgus requested that Georgia Tech fabricate at least one element for each of the two frequencies of interest and submit these to LMSC to be tested during the scheduled test period. Also during this trip, Tech personnel obtained detailed mock-up dimensions in order that an accurate model could be constructed. This model will be used in impedance and pattern measurements for the elements to be sent to Lockheed. The elements which have been considered by Georgia Tech as prime candidates for this application are:

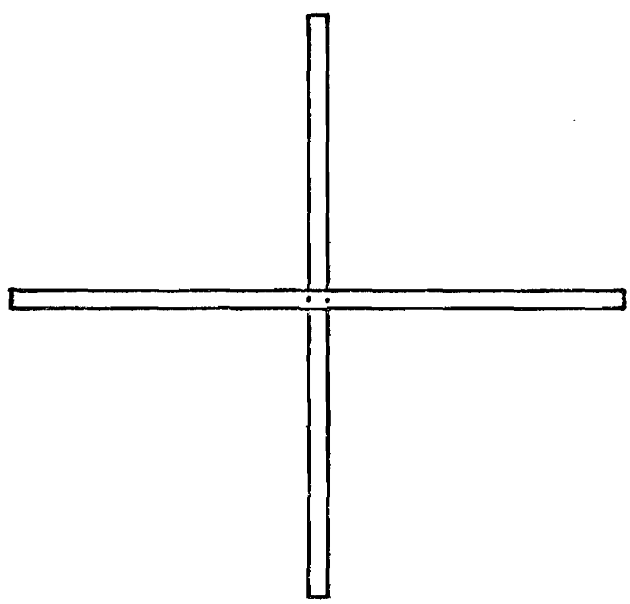
(1) flat spiral,
(2) crossed loops,
(3) crossed dipoles and variations thereof,
(4) flat plates, and
(5) quadrifilar helix.

The flat spiral is a basic laboratory instrument which is fairly small, circularly polarized, broadband, and commercially available. Georgia Tech recommended this antenna for use at 1600 MHz in the previously mentioned Final Technical Report. Lockheed personnel feel that its radiation (e. g. $\leq$ - 20 dB) at 90° away from its normal makes it a poor choice and indicated that they are looking for elements with broader patterns. It should be remembered that in a time diversity system only that portion of the pattern which is within $\pm$ 45° of normal in the roll plane is important since the other pair of elements would be utilized beyond that. Indeed, the fore and aft coverage about the vehicle would suffer from an element whose pattern falls off too rapidly; however, the problem could be remedied by placing an additional two elements on the vehicle with one pointed fore and one aft. In any case, Georgia Tech personnel have requested that LMSC include spirals in their collection of elements to be tested in the chamber.

The crossed loops which were recommended in the Final Report are shown in Figure 1. It was postulated that the half wavelength loop located over a ground plane would act as a one wavelength magnetic loop and radiate with its maximum field along the normal to the ground plane. Numerous single and crossed loops were fabricated and tested (VSWR and patterns) to verify the postulated performance. First, a single loop designed to resonate at 1.6 GHz was fabricated and its VSWR measured. This VSWR is shown as a function of frequency in Figure 2 (designated as "First Loop Only"). This loop resonated (w.r.t. a 50-ohm feed line) at approximately 1.6 GHz as designed, with a VSWR of approximately 1.5:1 or better. When the second loop was placed in its orthogonal position but terminated with a 50-ohm load, the best resonance point moved down to approximately 1.2 GHz with a corresponding degradation at 1.6 GHz as shown. Interchanging the feed point and termination verified that the two loops were performing similarly as shown in Figure 2. When the two loops were then fed simultaneously with a 3 - dB 90° hybrid, the pair appeared to have a very high VSWR at the previous single loop resonance point (1.2 GHz). A second pair of loops was fabricated and tested in an attempt to explain this phenomenon. As shown by the swept frequency VSWR for the three situations depicted as (a), (b), and (c) in Figure 3, the performance is similar. The loops appear to be strongly coupled with energy being fed into one loop and traveling down the transmission line of the other and back into the hybrid where a portion appears at the original input. A third pair of loops was fabricated which were orthogonal to but displaced from each other as shown in Figure 4 in an attempt to decouple the elements. The two loops were still strongly coupled but could be matched out with vertical grounded posts over the entire range of 1 to 2 GHz as shown in this figure. Radiation patterns of this scheme revealed a deep null on axis (for either sense circular) thereby casting suspicion on the theory of radiation by the half loop over a



(a) Single Element - Side View



(b) Dual Crossed Elements - Top View

Figure 1. Schematic diagram of half-loop over a ground plane showing (a) side view of a single element and (b) top view of dual crossed elements for generating circular polarization.

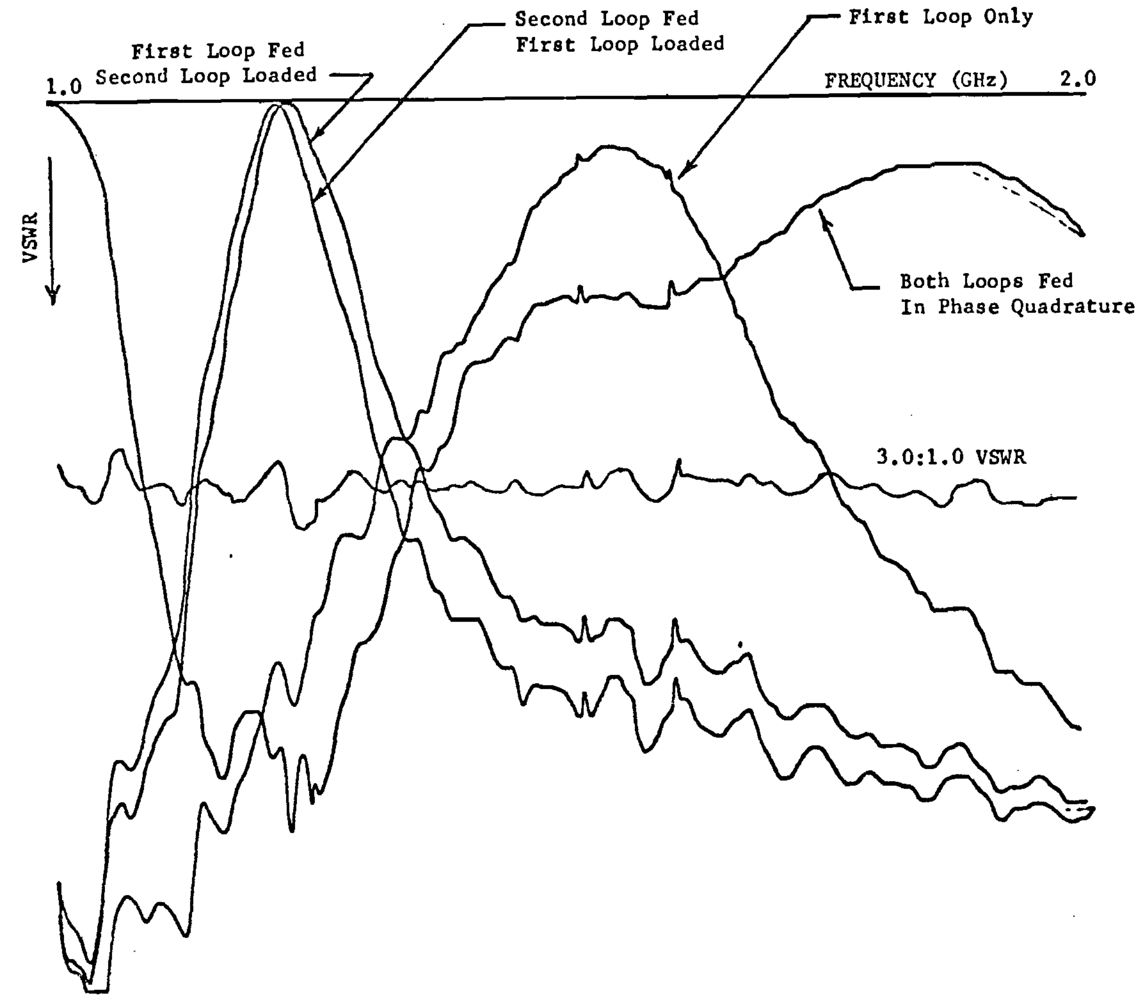


Figure 2. Swept frequency VSWR measurements for various combinations of half wavelength loops over a ground plane.

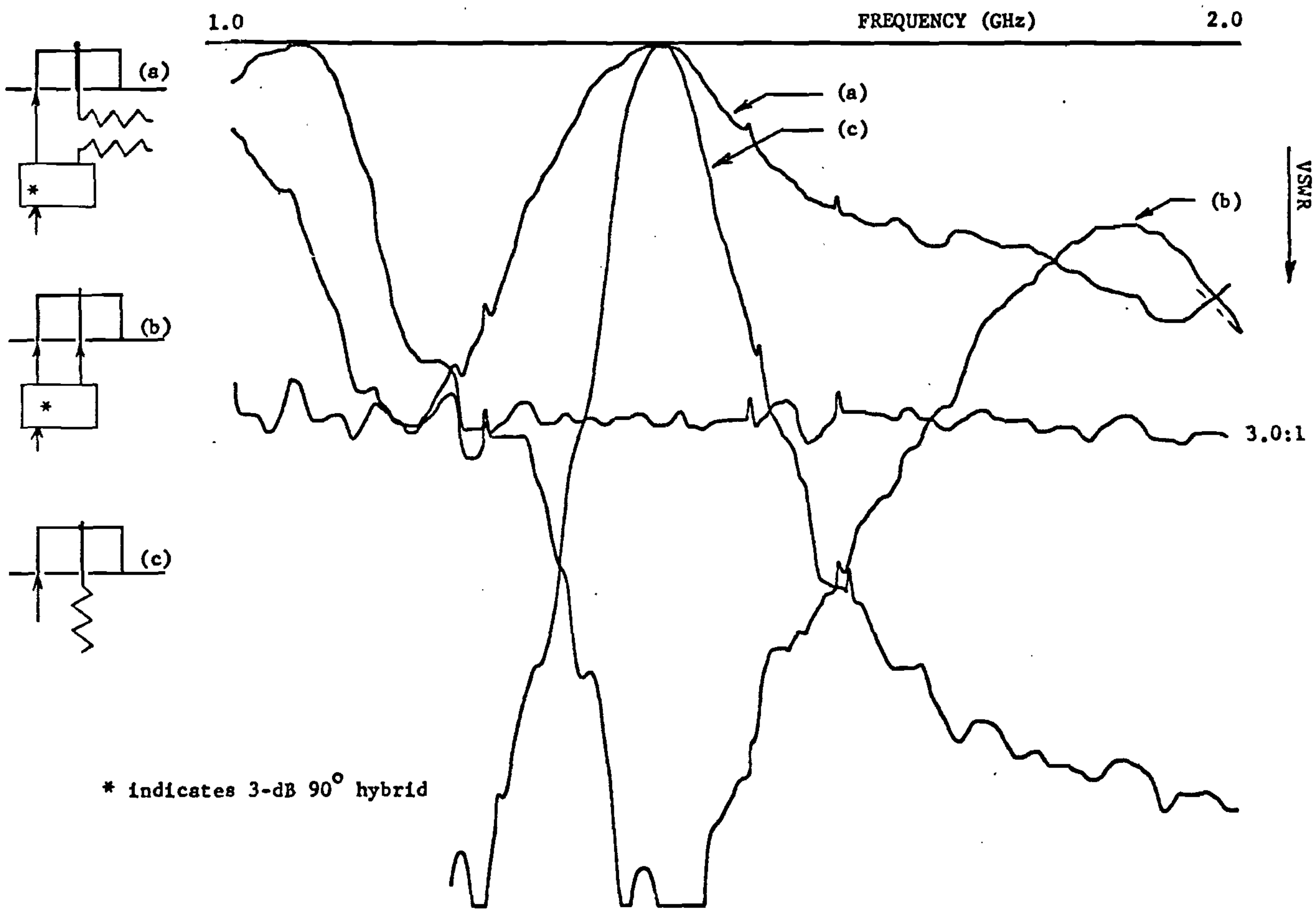


Figure 3. Swept frequency VSWR measurements for three configurations of crossed loops over a ground plane.

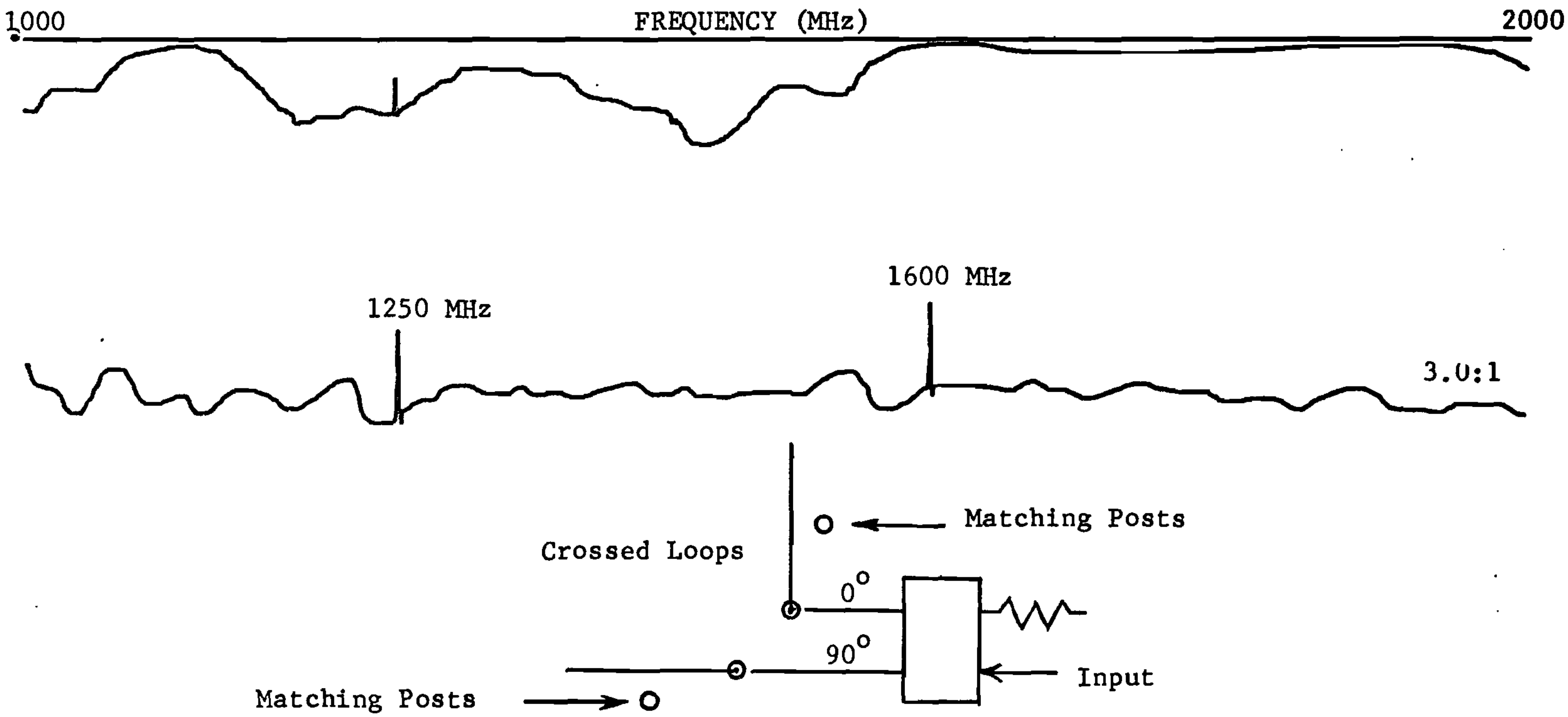


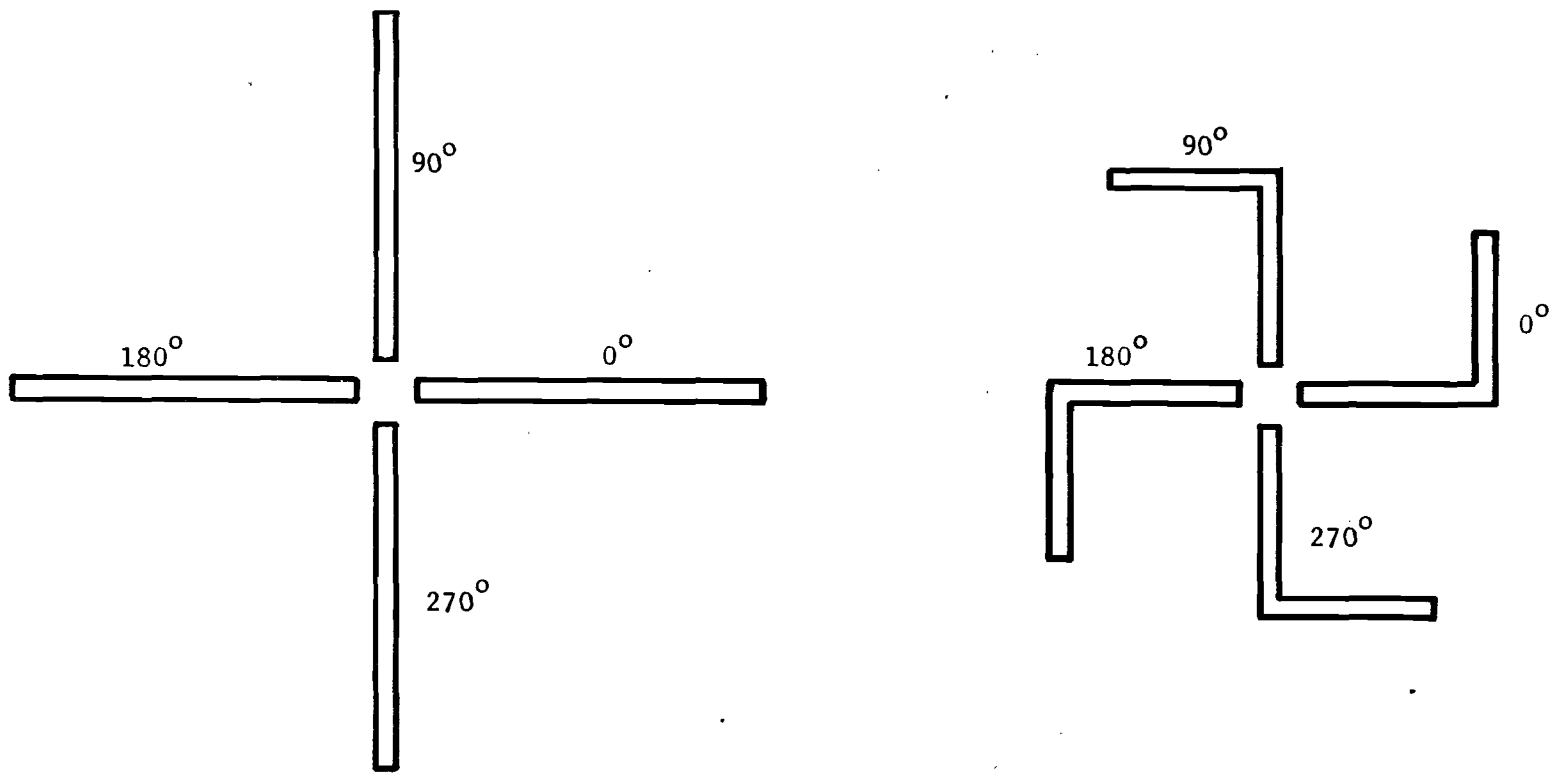
Figure 4. VSWR as a function of frequency for a breadboard pair of crossed loops over a ground plane. Copper matching posts are located as shown.

ground plane. Several single loops were then fabricated and their patterns measured at the resonance frequency. All of the loops were placed one eighth of a wavelength or less away from the ground plane, and in all cases, a pattern in the plane of the loop revealed a dip or null in the radiation along a direction normal to the ground plane. If the loop were indeed acting as a magnetic element, the ground plane separation distance would be of little importance; however, an electric field element must be one quarter of a wavelength away to receive maximum reinforcement from its image. The patterns indicate that the loop is probably functioning as an E-field element. The loop was not given further consideration as a 1600 MHz element since it cannot be a half wavelength long and one quarter wavelength above the ground plane simultaneously unless the portion of the loop parallel to the ground plane approaches zero length.

The second type of element considered was the familiar configuration of crossed dipoles over a ground plane. Several dipoles were tested including the planar orthogonal elements in Figure 5 (a), the bent dipoles or "swastika" in Figure 5 (b), and a modified swastika formed by bending the outside portion of the dipole down to make an angle of 45° with the ground plane. In each case, the elements were fed with a 90° phase progression from the previous element so as to produce circular polarization. All of the dipoles investigated were placed at a quarter wavelength above the ground plane and produced circularly polarized patterns as shown in Figure 6. The radiation pattern was virtually the same in each of the three major configurations examined. These patterns show that the crossed dipoles produce essentially the same radiation as the flat spiral (i.e. -20 dB at 90° away from boresight) but without the spiral's bandwidth; consequently, the crossed dipoles appear to offer no unique advantages.

The third type of element investigated was suggested by Dr. Kilgus and consists of two parallel plates shorted in the center and fed by four symmetrically located feeds as shown in Figure 7. The antenna has been reported to be circularly polarized with a cardioid shaped radiation pattern. Several different sizes of plate pairs were fabricated and tested. Swept frequency VSWR measurements are shown in Figure 8 for three such pairs of plates. Obviously, decreasing the size of both plates with all other factors held constant increases the resonance frequency. It was also observed that shortening the length of the one inch shorting bar by one-sixteenth of an inch increased this frequency by a few MHz. A 400 MHz breadboard model was fabricated by capacitively loading (between 2 and 10 picofarads) a pair of 7.5 inch square plates. The radiation pattern for this configuration was considered unacceptable since its radiation was symmetrical in the front and back hemispheres, had its peak along a direction parallel to the plates and a dip along the normal to the plates. It is believed that this performance is a consequence of the fact that the antenna is itself symmetric in both hemispheres, and that an antenna having the top plate smaller than the bottom plate would direct more energy into the front sector. During the month of September, such an antenna will be fabricated and tested for use at 400 MHz and will be forwarded to LMSC if its performance is suitable.

No element has been found yet which has a 90° taper of 10 dB or less at 1600 MHz; consequently, that investigation will continue. It is felt that the quadrifilar helix is a prime candidate for this application since it is circularly polarized and has a very broad beamwidth. Several quadrifilars will be fabricated during the coming month to demonstrate its



(a) Orthogonal Crossed Dipoles

(b) Swastika

Figure 5. Conceptual schemes for obtaining circular polarization from crossed dipoles.

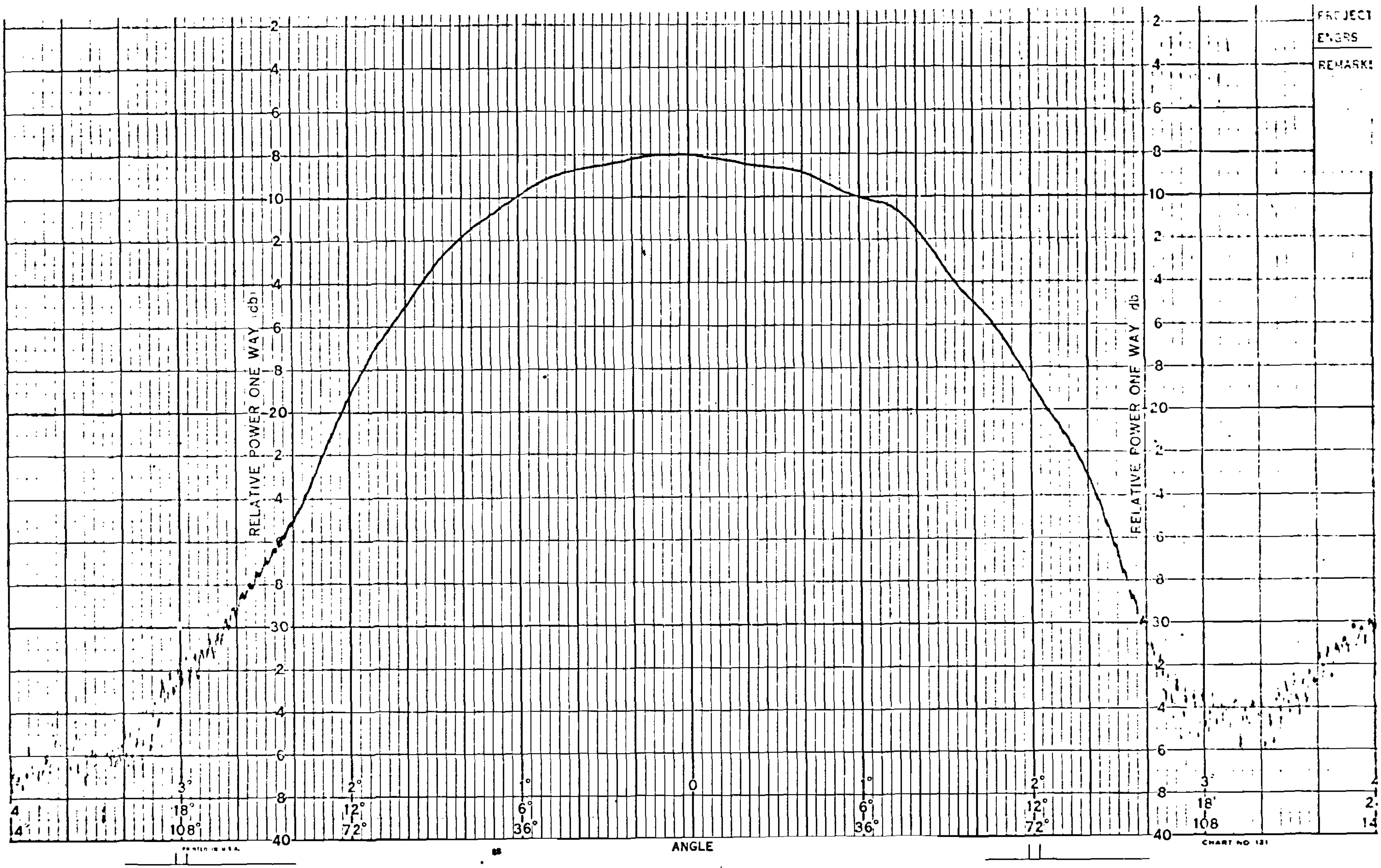


Figure 6. Principal plane radiation pattern of a circularly polarized pair of crossed dipoles (four elements) over a ground plane.

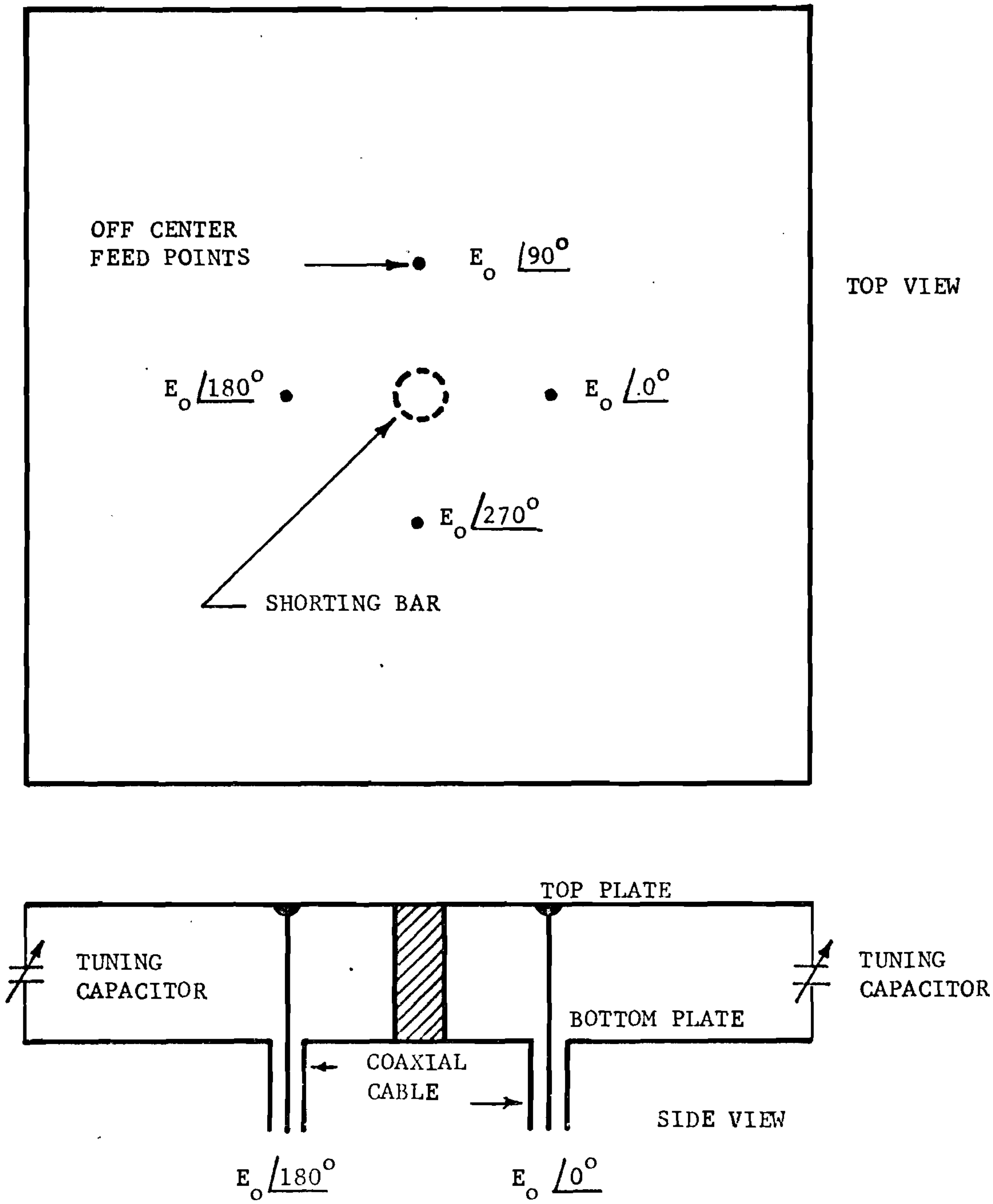


Figure 7. Simplified geometry of the circularly polarized flat plate antenna.

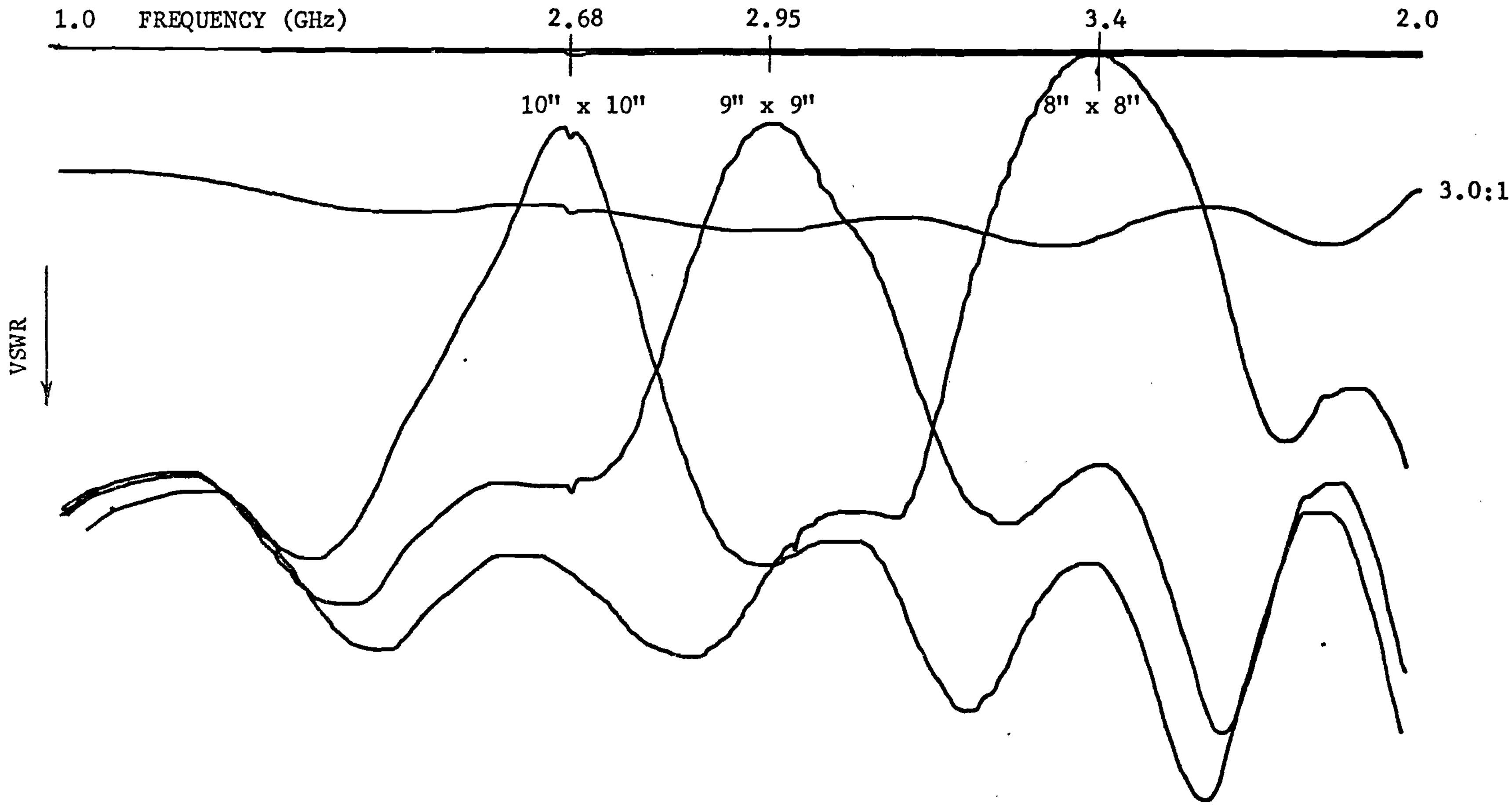


Figure 8. VSWR as a function of frequency for three separate pairs of shorted parallel plates having the plate dimensions shown and a one-inch plate spacing.

applicability at his frequency.

A wood and sheet metal mock-up of the SATRACK vehicle was fabricated during the month of August from the dimensions obtained from Lockheed. This mock-up is useful in determining the possible changes in element impedance and pattern when Georgia Tech elements are placed on the SATRACK vehicle.

It is felt that the time diversity scheme will definitely improve the coverage at both frequencies; however, no estimate of the improvement has been made. For this reason, computer calculations (scalar) will be made during the forthcoming month to determine this improvement.

As of 1 September 1974, all of the contract funds ($24,957) have been expended along with an additional $3,094.85 which has been encumbered against the anticipated follow on effort to the SATRACK program. The new funding should be retroactive to 15 August 1974, the previous contractual deadline, so as to cover all work performed on the program.

During the forthcoming report period, the element development will be continued and at least one element pair at each frequency will be forwarded to Lockheed. These elements will most likely be parallel plates at 400 MHz and quadrifilar helices at 1600 MHz. Georgia Tech will also investigate the possibility of stacking two pairs of parallel plates so as to locate elements for both frequencies on a common surface area. The theoretical time diversity coverage calculations will also be performed.

Respectfully submitted,

James W. Cofer, Jr.
SATRACK Project Director
A-1617-100

JWC:jm

Approved:

R. M. Goodman, Jr., Chief
Sensor Systems Division

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

2 October 1974

Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task 2
(SATRACK Study)

Subject: Monthly Contract Technical Status Report No. 6
covering the period 1 September through 30 September 1974

Gentlemen:

This is the sixth Monthly Progress Summary under the referenced contract and covers the period 1 September through 30 September 1974.

During this report period, major efforts were directed toward fabrication of elements for use at 400 and 1600 MHz, namely flat parallel plates and quadrifilar helices, respectively. Breadboard pairs of each of these element types were fabricated, tested, and forwarded to Mr. Frank Butscher of LMSC for testing on the LMSC mockup in their anechoic chamber.

Two quadrifilar helices were fabricated which utilized infinite baluns and single feed points (i.e. no quadrature hybrids). One such element is shown in Figure 1. Two helices were designed to operate at 1.6 GHz but actually resonated at about 1.62 GHz as shown by the swept frequency VSWR measurement for element #1 in Figure 2. This measurement which was performed for a single element in an anechoic chamber was repeated for the element positioned in the opening of the impedance mockup (see Figure 3), and the results are shown in Figure 4. Radiation patterns both for the single element and the element on the mockup are shown in Figures 5 and 6, respectively. It is believed that the dip in the radiation pattern along the helix axis as shown in Figure 5 is due to the effect of the eight-inch ground plane. This same type of performance is also exhibited when the element is placed on the mockup; however, the vehicle itself modifies the pattern as shown in Figure 6. The Georgia Tech partial mockup does not introduce as much optical blockage of the element pattern as will the full mockup; consequently, much of the radiation which occurs beyond 90° should be lower in the full scale tests. The peak gain for both of these patterns is about 1 dB w.r.t. linear (-2 dB w.r.t. circular).

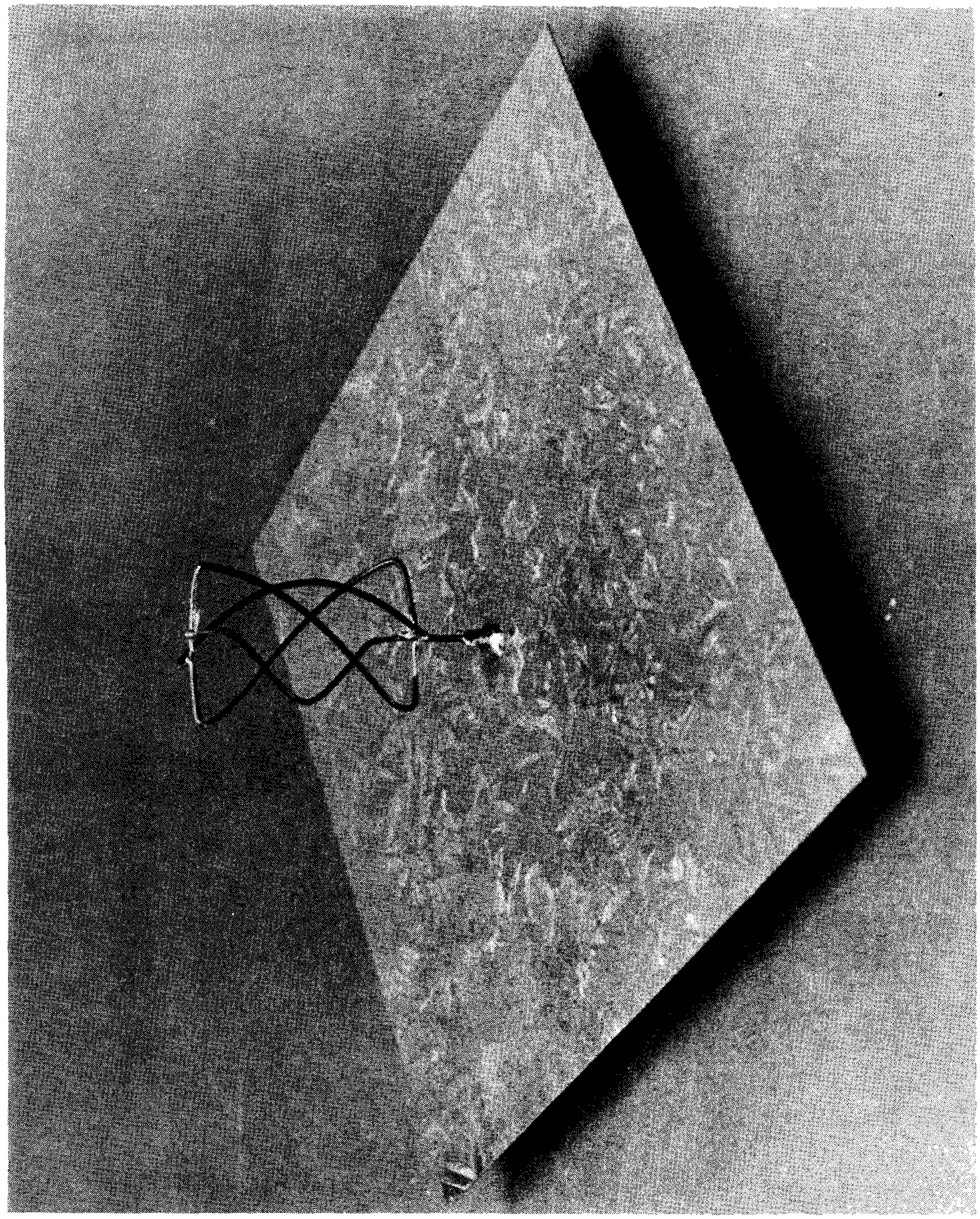


Figure 1. Photograph of infinite balun quadrifilar helix for use at 1600 MHz. Ground plane is eight inches square.

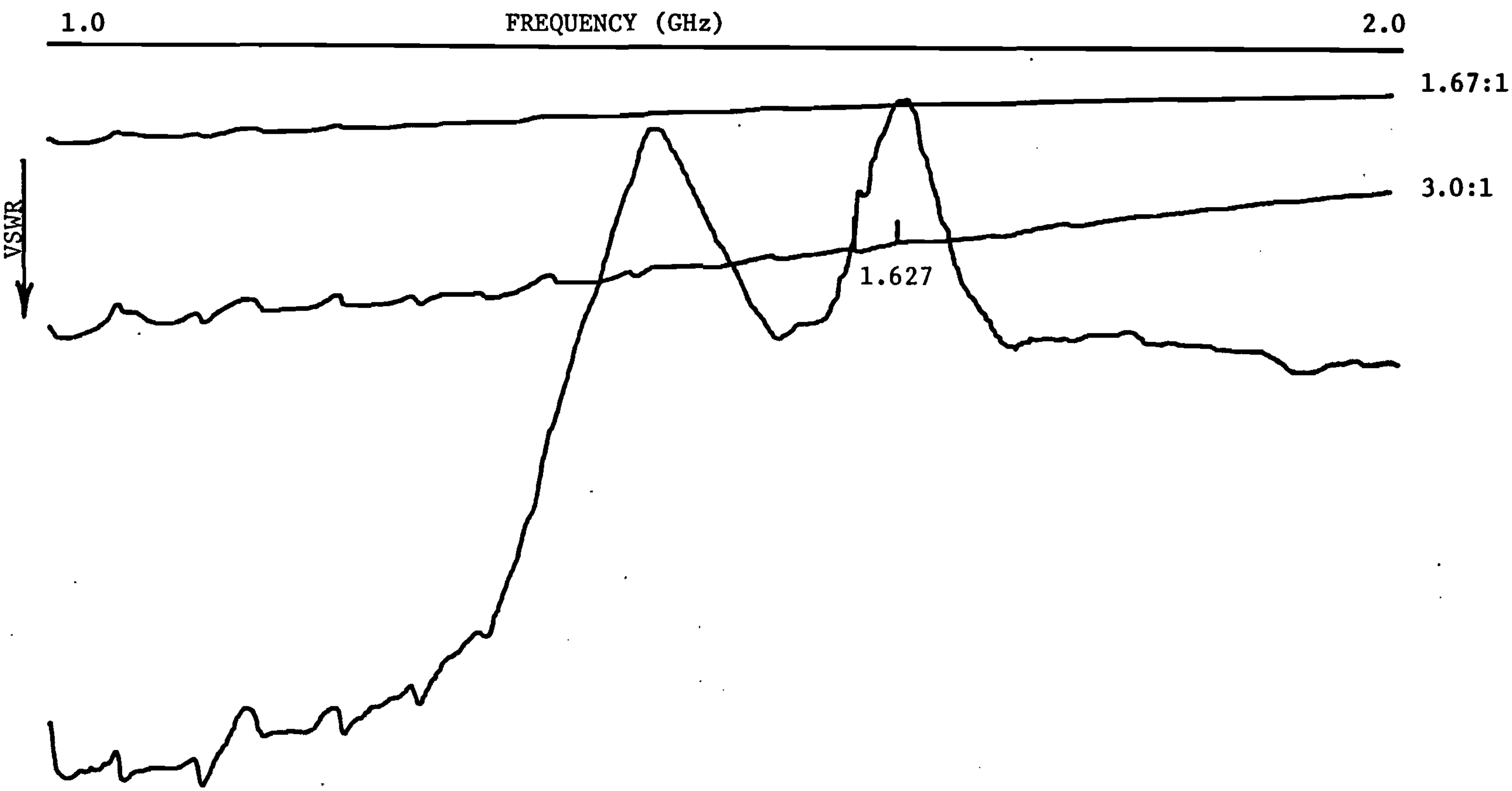


Figure 2. Measured swept frequency VSWR for quadrifilar helix #1 in free space.

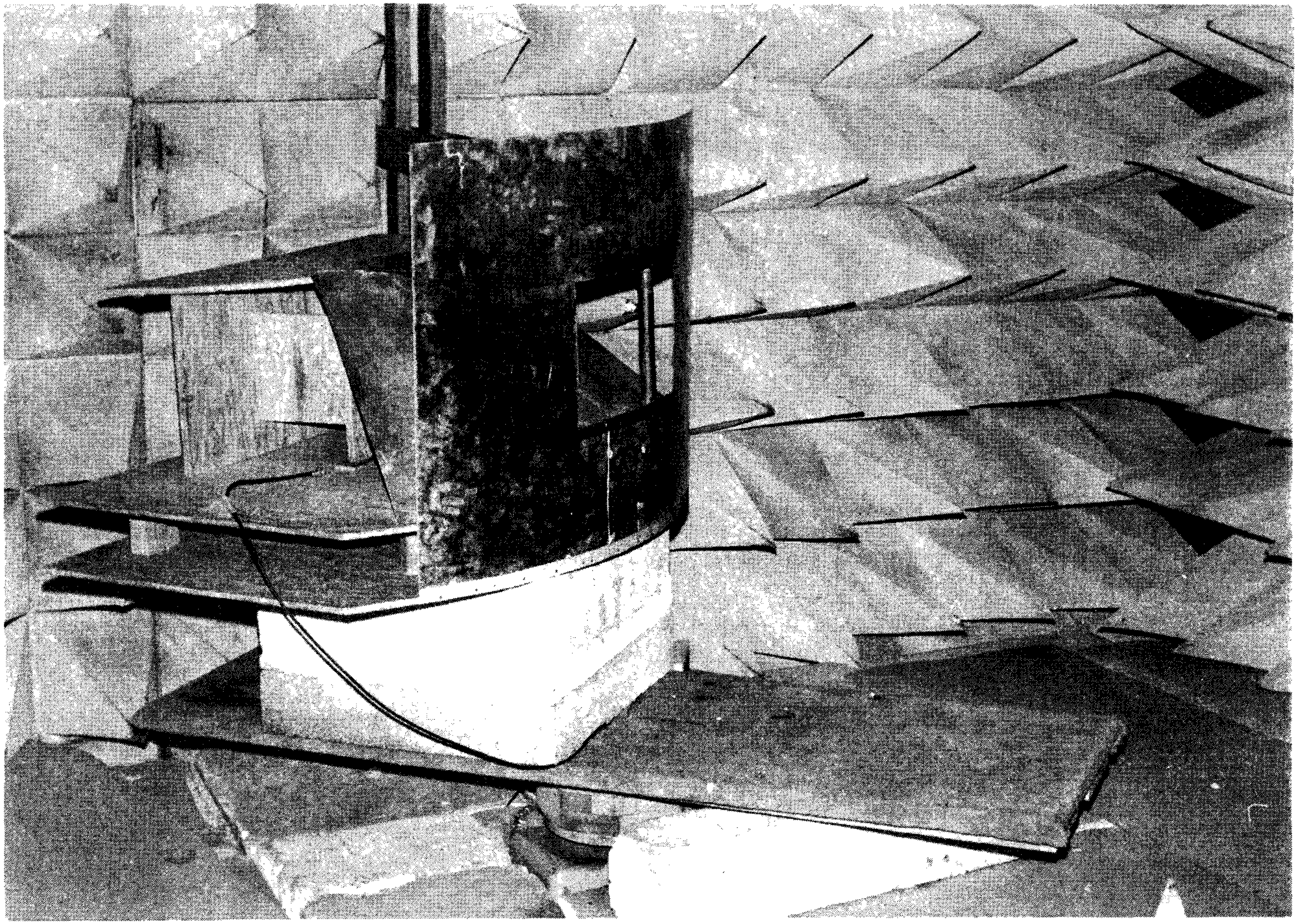


Figure 3. Georgia Tech impedance mockup in anechoic chamber.

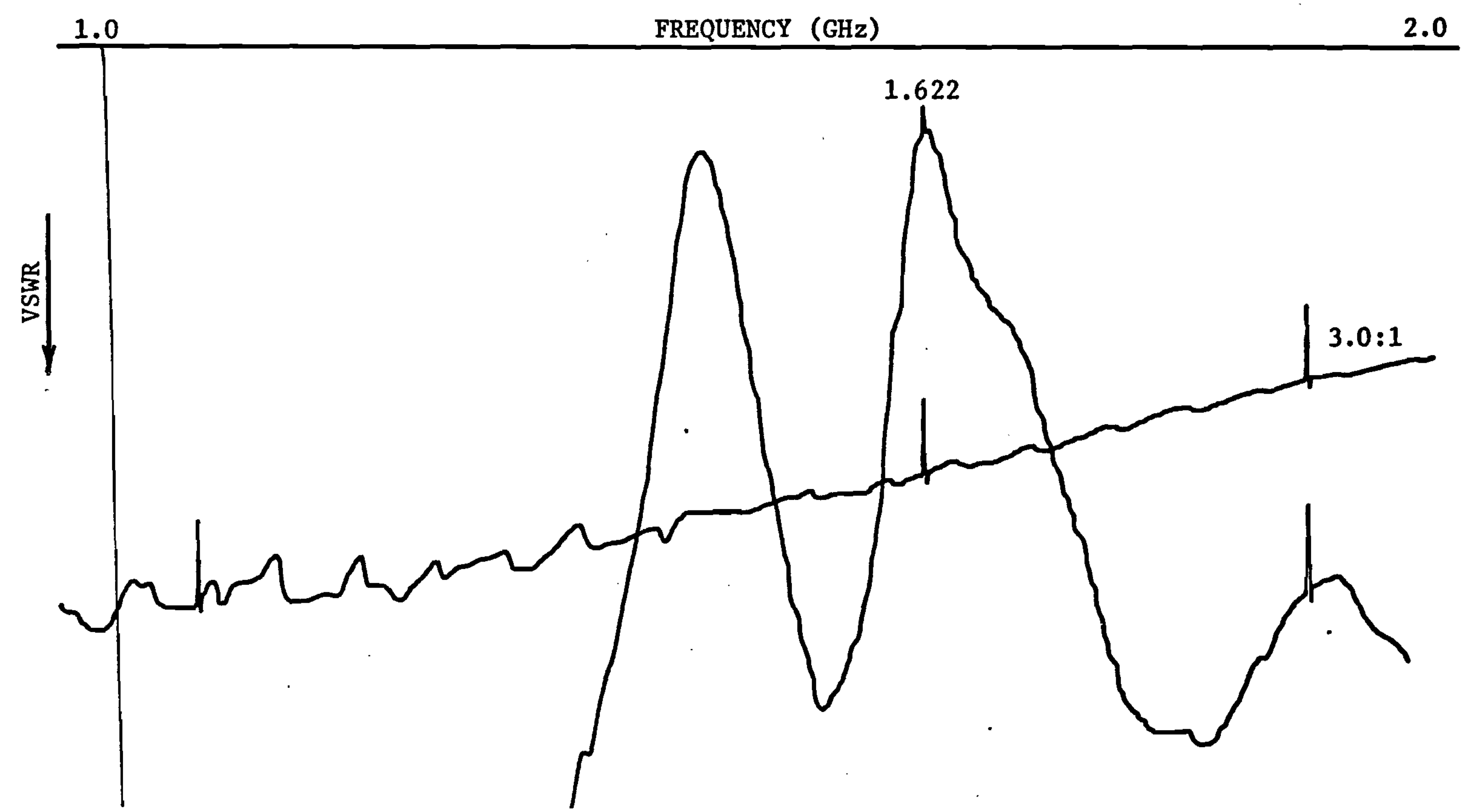


Figure 4. Measured swept frequency VSWR for quadrifilar helix #1 located on the Georgia Tech mock up.

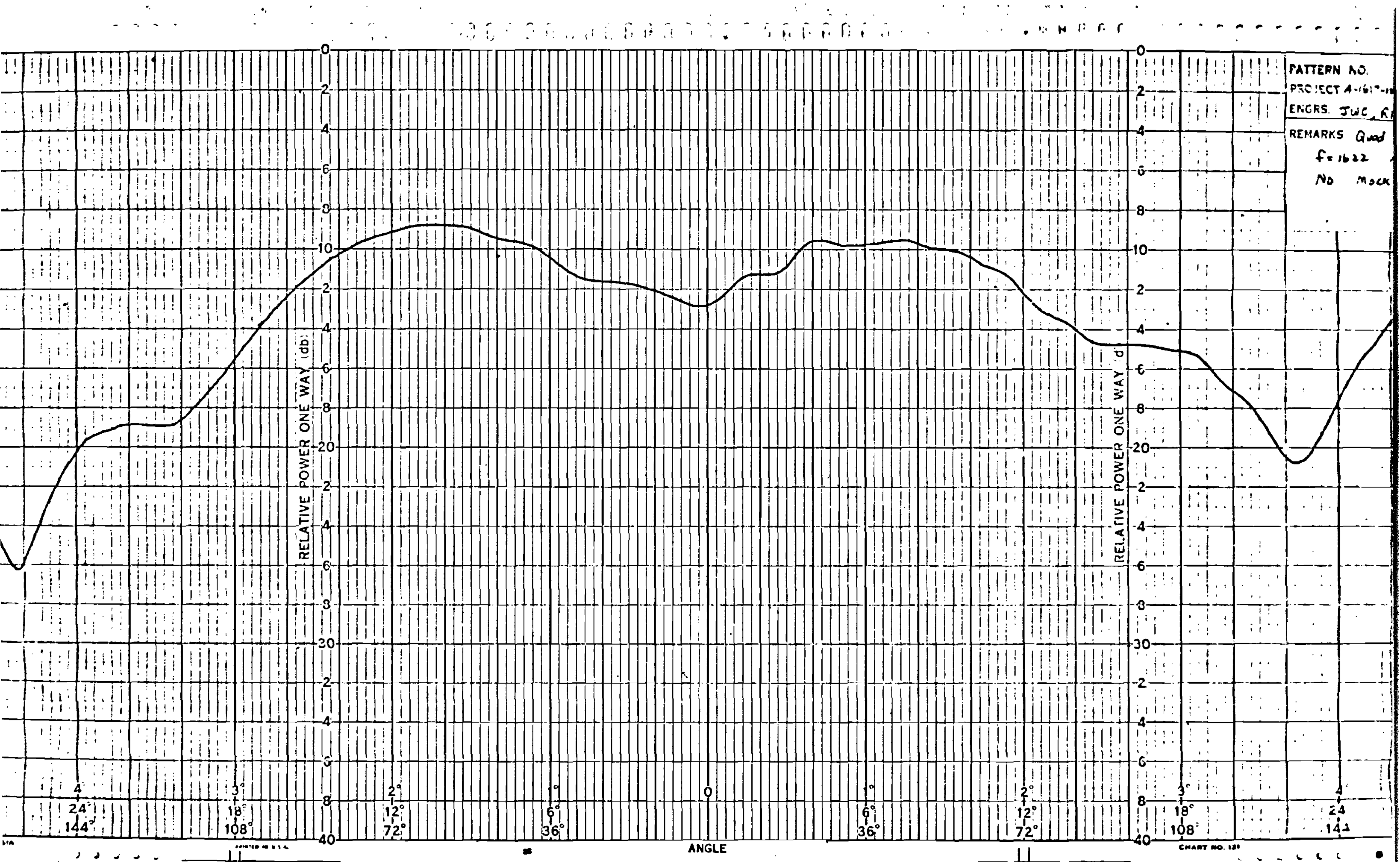


Figure 5. Measured radiation pattern of quadrifilar helix #2 operating at 1600 MHz above on eight inch square ground plane.

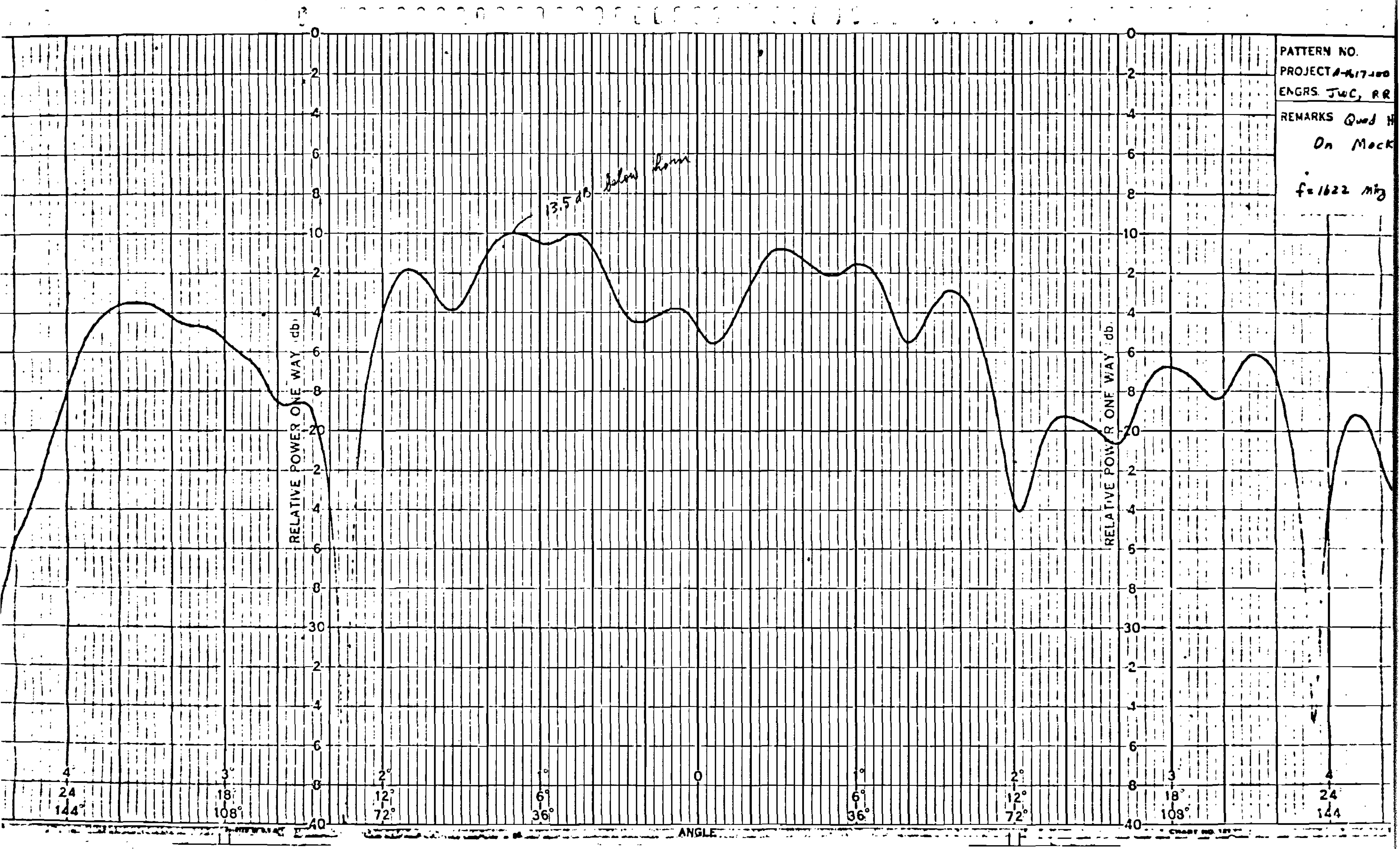


Figure 6. Measured radiation pattern of quadrifilar helix #2 operating at 1600 MHz on the Georgia Tech mockup.

Also during this report period, several parallel plate antennas similar to the one depicted in Figure 7 of the August Technical Status Report were fabricated. In general, such antennas require three hybrids (one 90° and two 180°) for proper phasing to achieve circular polarization. Several experiments were also performed for a circular version of this type of antenna with only two orthogonally placed feed points as shown in Figure 7. The two feed lines are strongly coupled; consequently, the antenna cannot be matched by feeding each channel separately. Rather, the tuning chpacitors must be adjusted while monitoring the swept-frequency reflections in the two feed lines simultaneously as shown in Figure 8. Two circular flat plate antennas (see Figure 9) were fabricated which consisted of a five-inch plate over an eight-inch plate separated by a one-half inch thick disk of polystyrene. Four tuning capacitors (2-8 pfd.) were placed along radial lines which form an angle of 45° with the radial lines through the feed points. The dielectric serves to make the cavity between the plates appear larger and also to provide a non-conducting mechanical connection between the plates. The swept frequency VSWR for each of the input ports to these elements are shown in Figures 10 and 11 for plate pair #1 and #2, respectively. The best match obtained was on the order of 1.3:1 for #1 and 1.6:1 for #2. Each had a 2.0:1 VSWR bandwidth of approximately 5 MHz. The radiation pattern for element #1 is shown in Figures 12 and 13 for the element only and the element on the Georgia Tech mockup, respectively. It was felt that the gain and coverage obtained were acceptable; therefore, the elements were forwarded to Lockheed for testing.

It should be noted that Figure 8 of the August Technical Status Report contained a mislabelled frequency axis. A corrected version of this figure is included here as Figure 14.

The effect of combining two orthogonal pairs of elements in a time-diversity manner as opposed to a four-element coherent addition was also investigated at 1600 MHz. Patterns and their corresponding statistics were calculated for two and four element arrays and a four element time diversity array for element patterns having horizon (90° away from boresight) tapers of 5, 10, and 20 dB. Three dimensional patterns are shown for the three array configurations and 20-dB horizon taper in Figures 15, 16, and 17. Percent coverage levels for these three patterns are plotted for comparison in Figure 18. At the ninety percent coverage level time diversity provides about 4 dB improvement over the four element array and 9 dB over the two element array with 20-dB element tapers. In addition, the radiation pattern for the time diversity case is much smoother than for the four element array.

As of 1 October 1974, all of the original SATRACK (Task 2) contract funds ($24,957) have been expended along with an additional $7,367.69 which has been encumbered against the anticipated follow on effort. Although not during this report period, it was learned on 2 October that a $25,000 increment of the anticipated follow on effort had been received by Georgia Tech.

During the forthcoming report period, the element development effort will be continued. At least two more helices will be wound and their

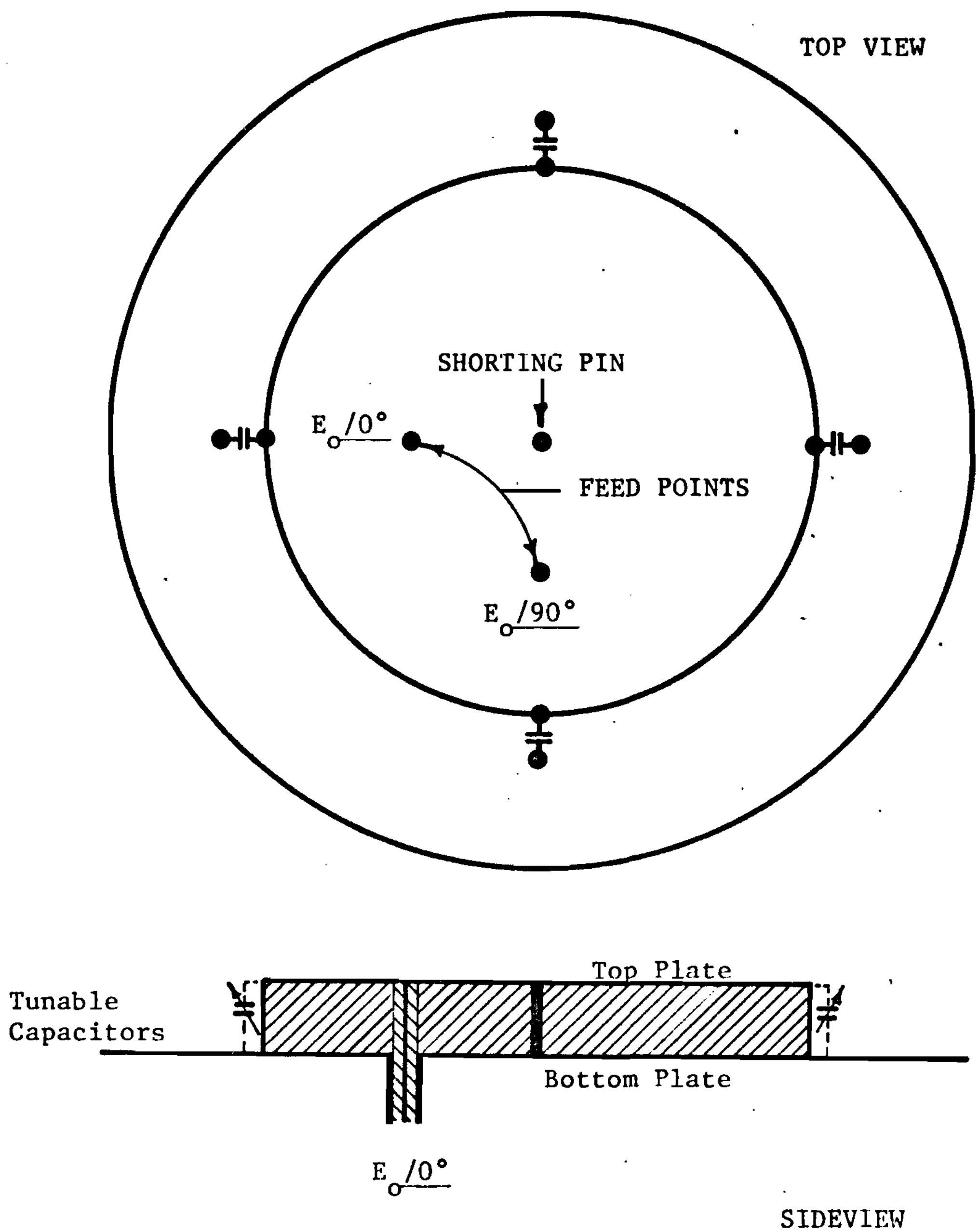


Figure 7 . Simplified drawing of circularly polarized parallel plate antenna.

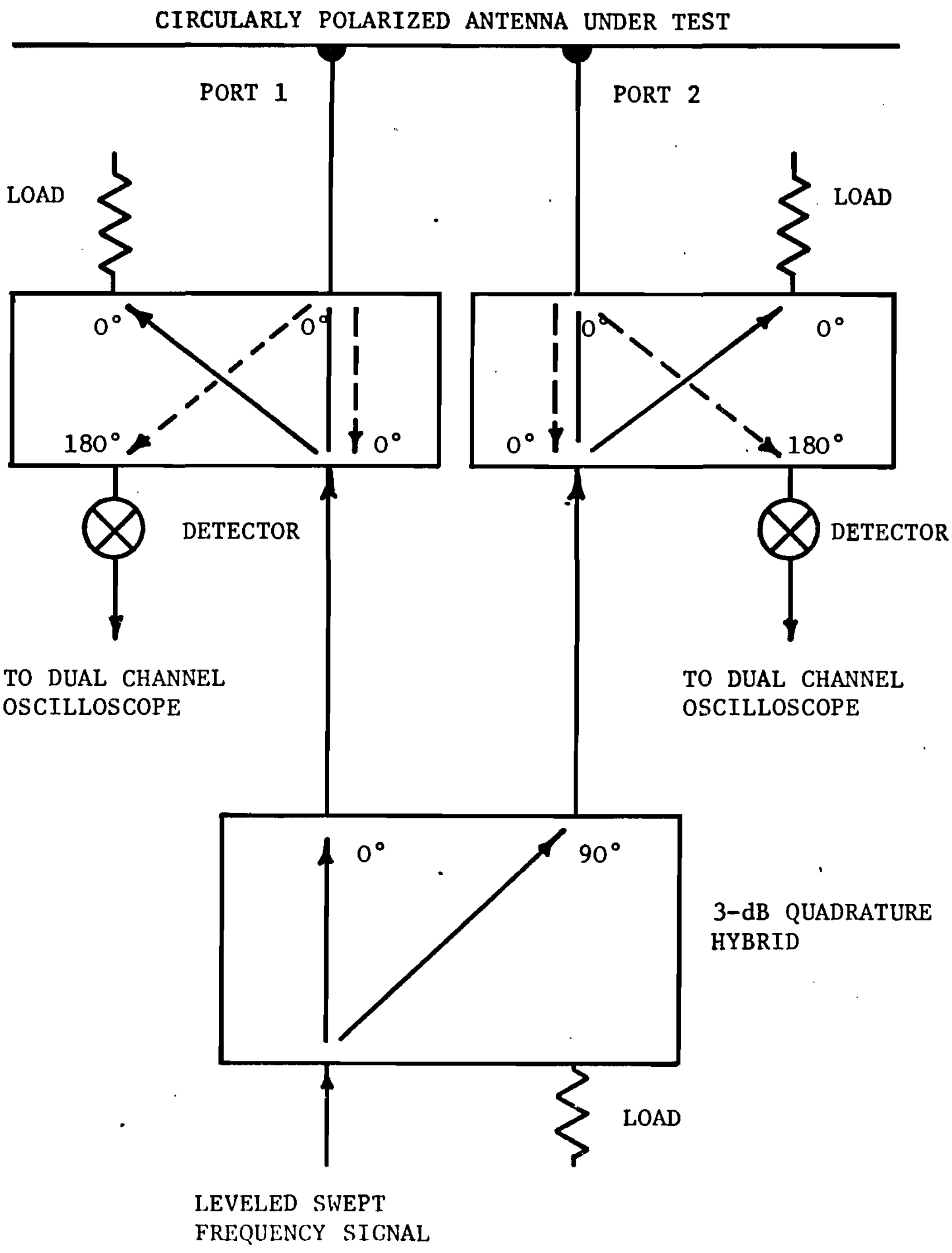


Figure 8. Simplified schematic diagram of instrumentation for matching two channels of a circularly polarized antenna simultaneously. All components beyond the quadrature hybrid should be identical in each channel.

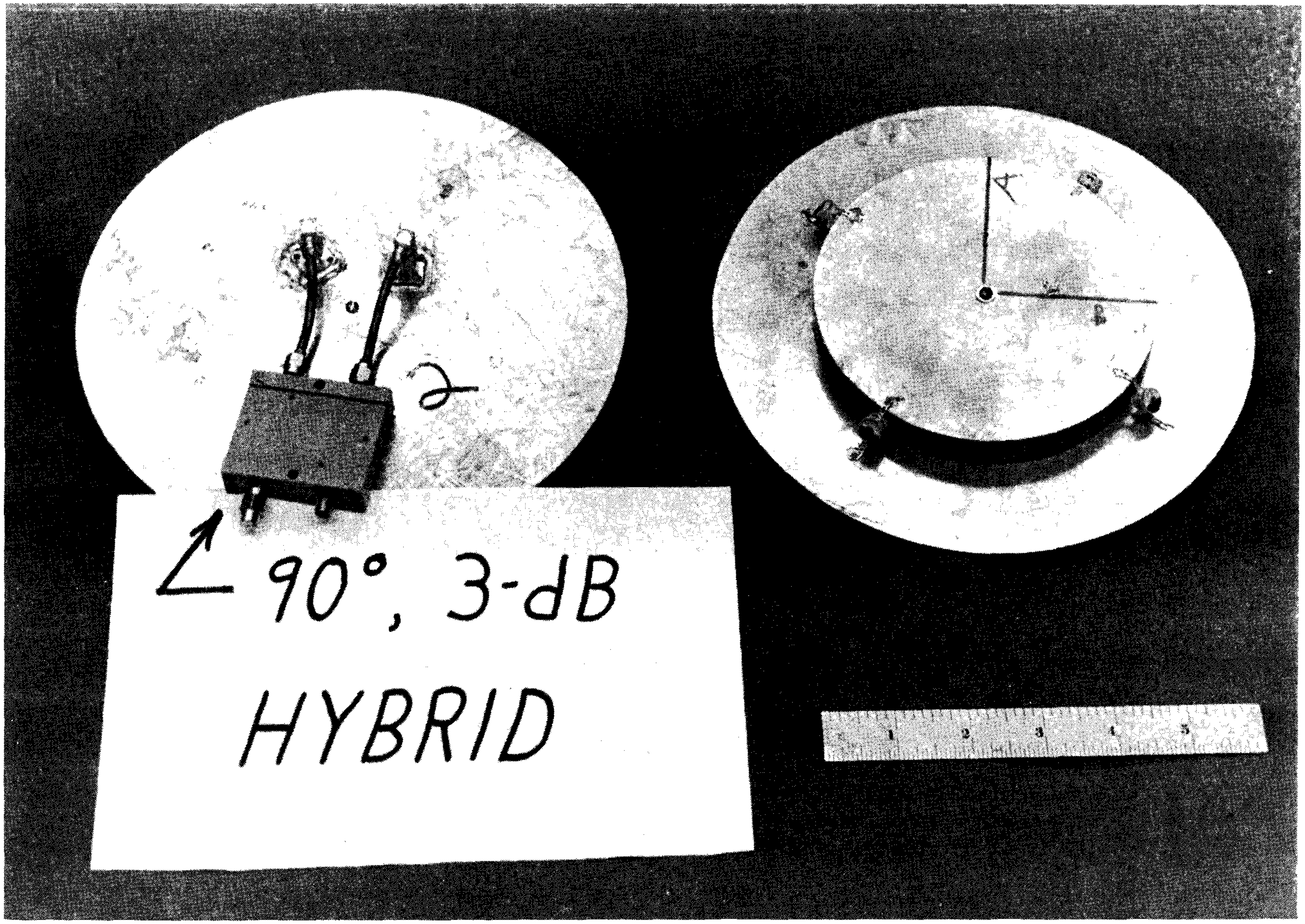


Figure 9. Front and rear views of 400 MHz circularly polarized flat plates.

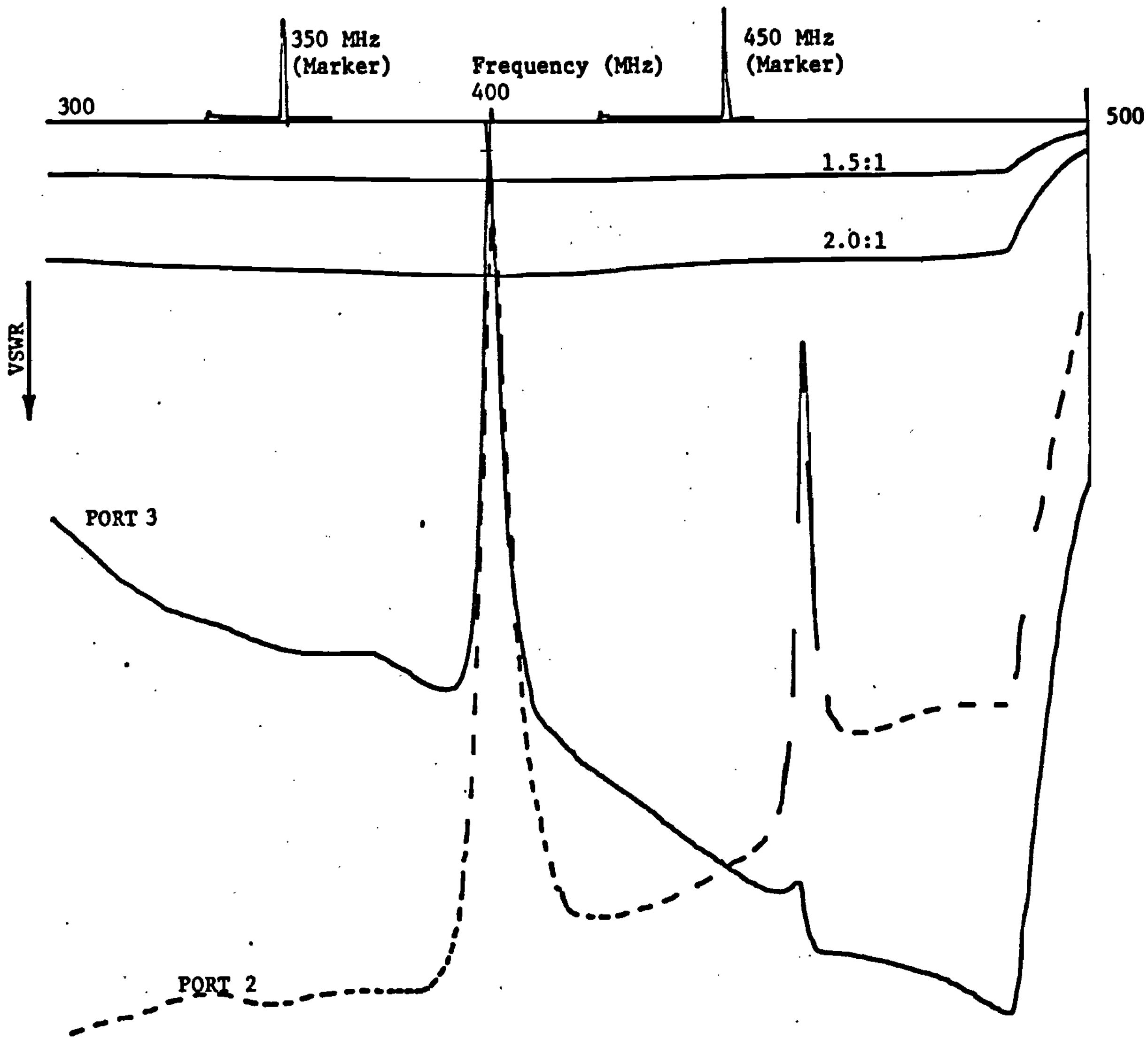


Figure 10. Swept frequency measured VSWR for the two ports of 400 MHz element #1 using the measurement set-up shown in Figure 8. Each element consists of a 5-inch circular plate over an 8-inch plate with two orthogonally positioned feeds fed in phase quadrature.

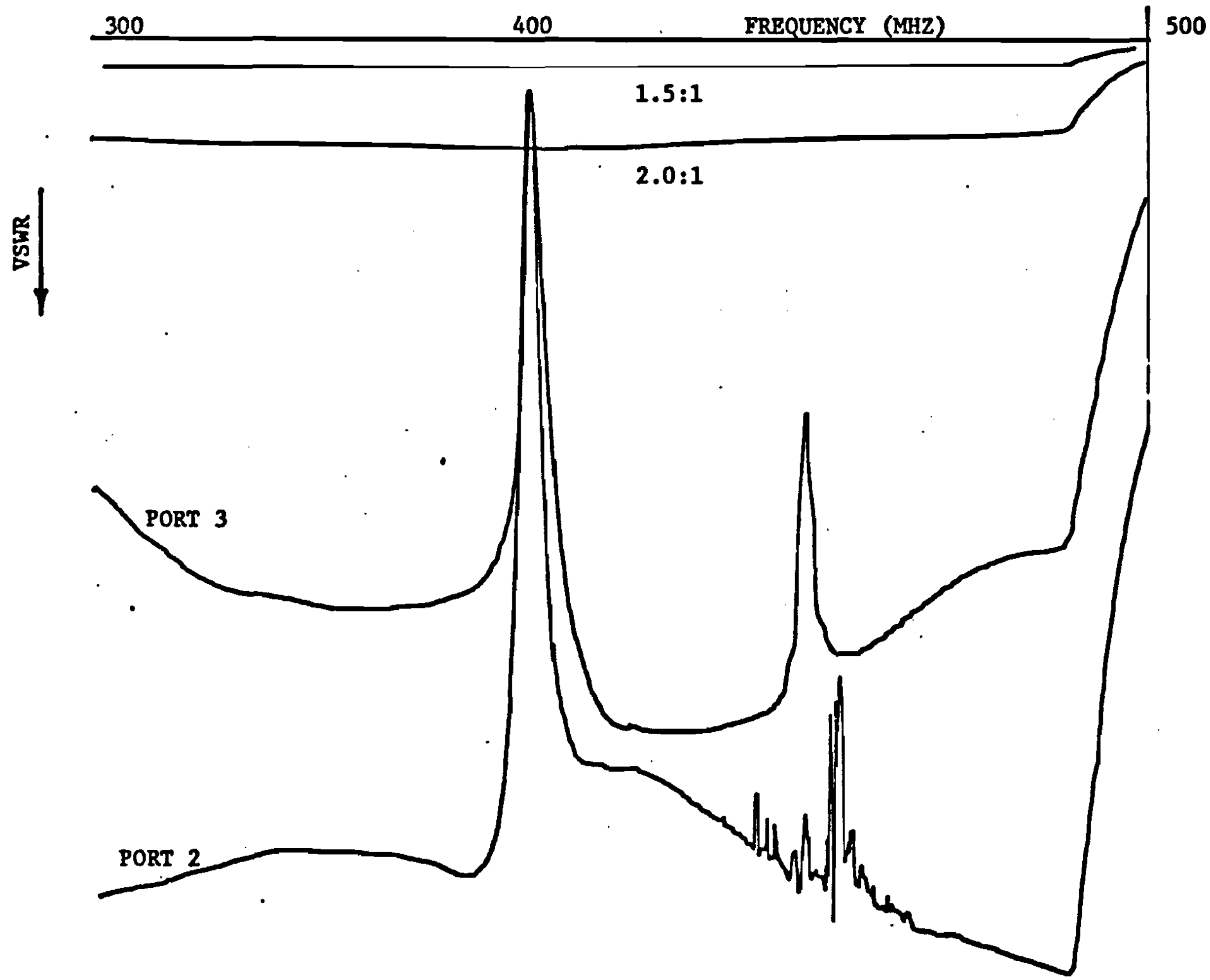


Figure 11. Swept frequency measured VSWR for the two ports of 400 MHz element #2 using the measurement set-up shown in Figure 8. Each element consists of a 5-inch circular plate over an 8-inch plate with two orthogonally positioned feeds fed in phase quadrature.

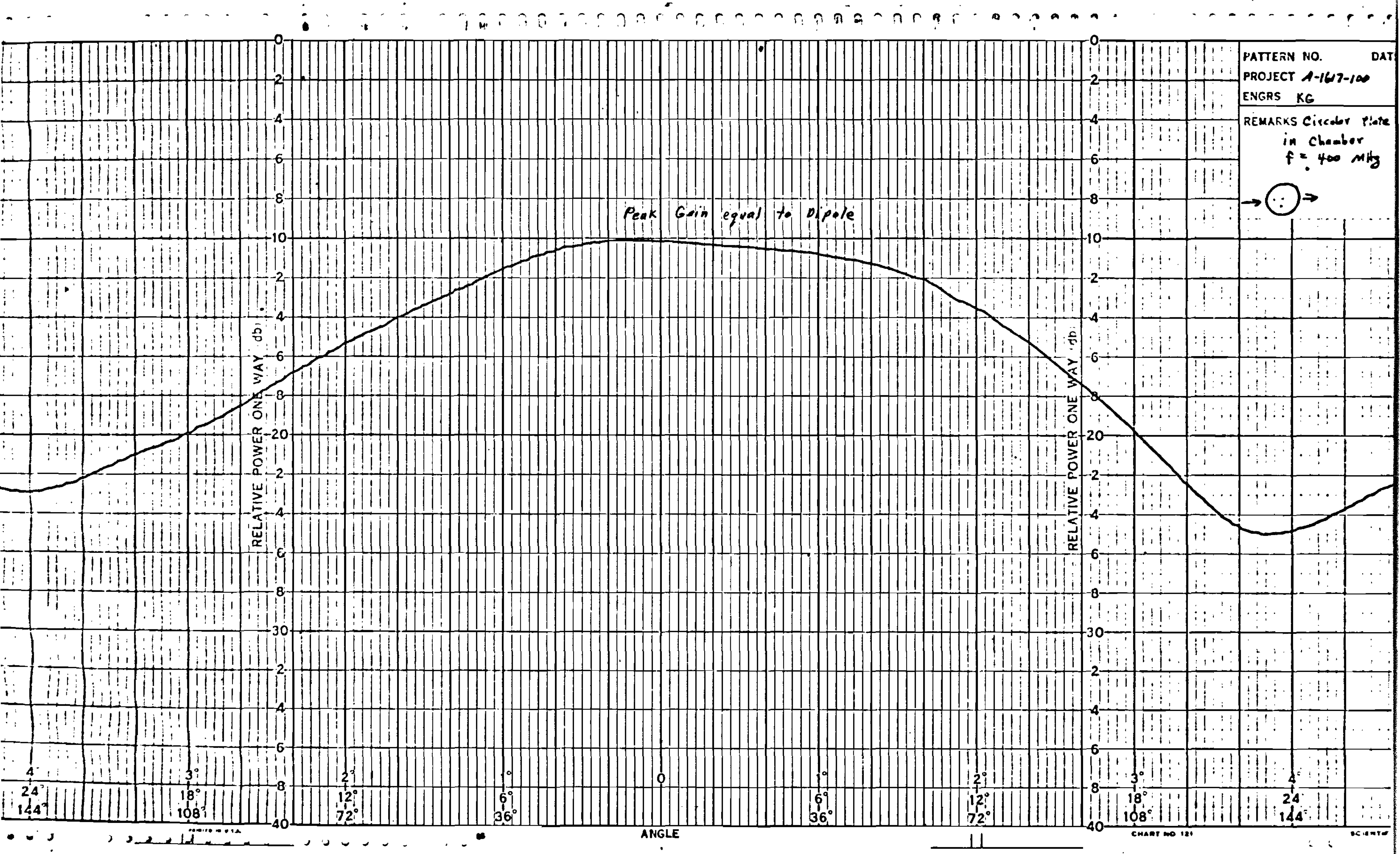


Figure 12. Lefthand circularly polarized radiation pattern for circular plate #1 operating at 400 MHz. Peak gain is approximately - 1 dBi LHCP.

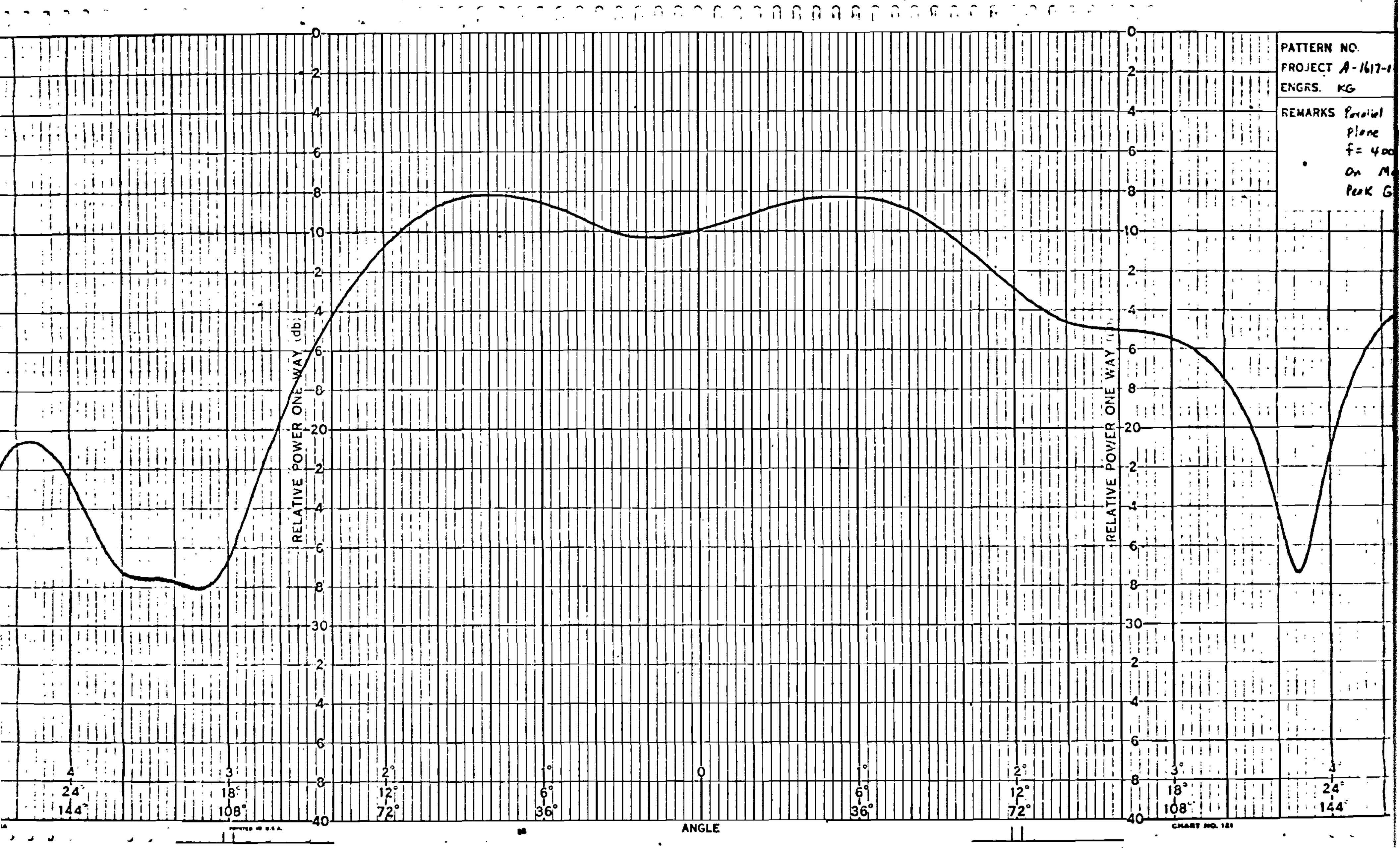


Figure 13. Lefthand circularly polarized radiation pattern for circular plate #1 operating at 400 MHz on the Georgia Tech mockup.

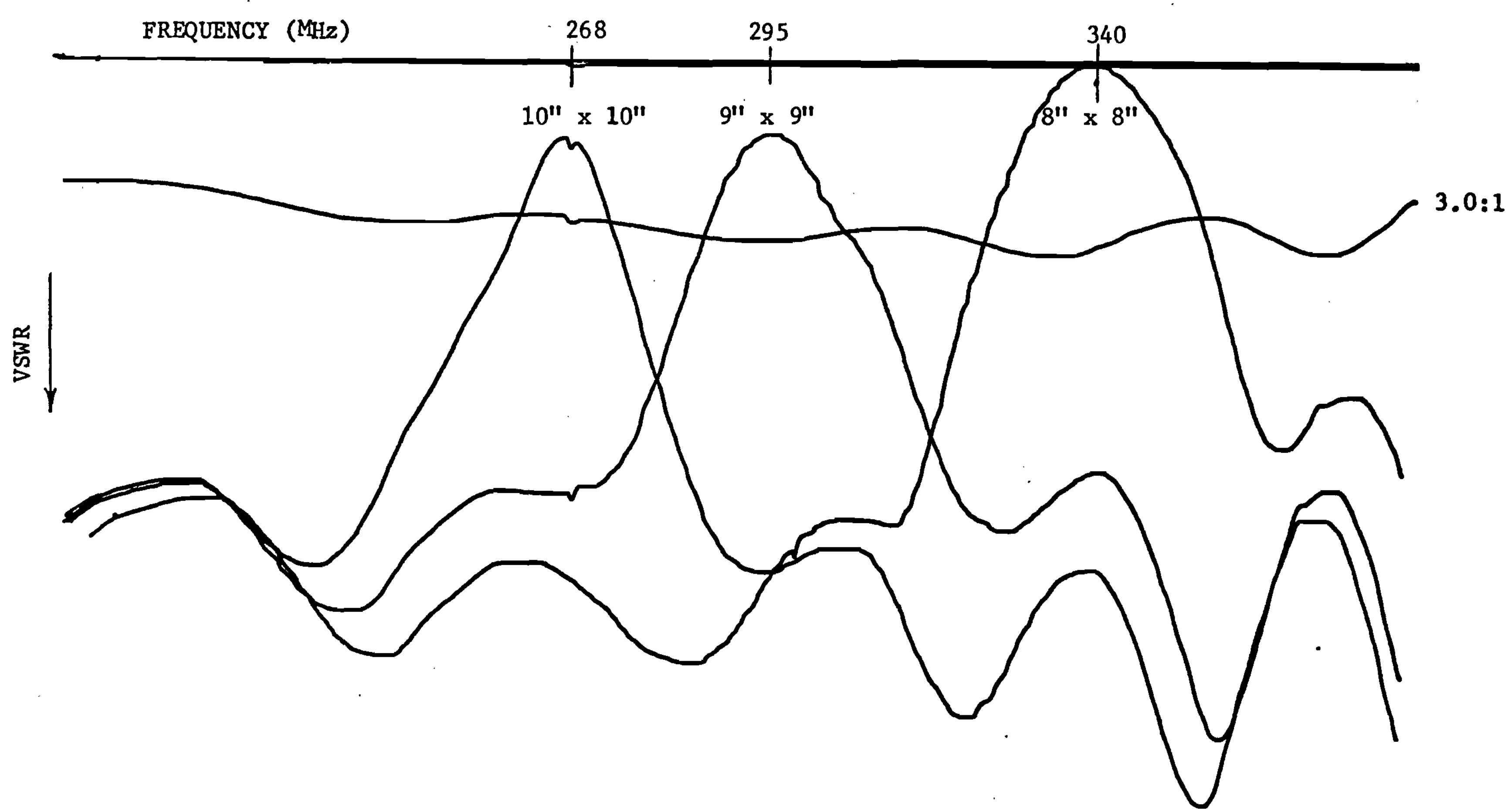


Figure 14. VSWR as a function of frequency for three separate pairs of shorted parallel plates having the plate dimensions shown and a one-inch plate spacing.

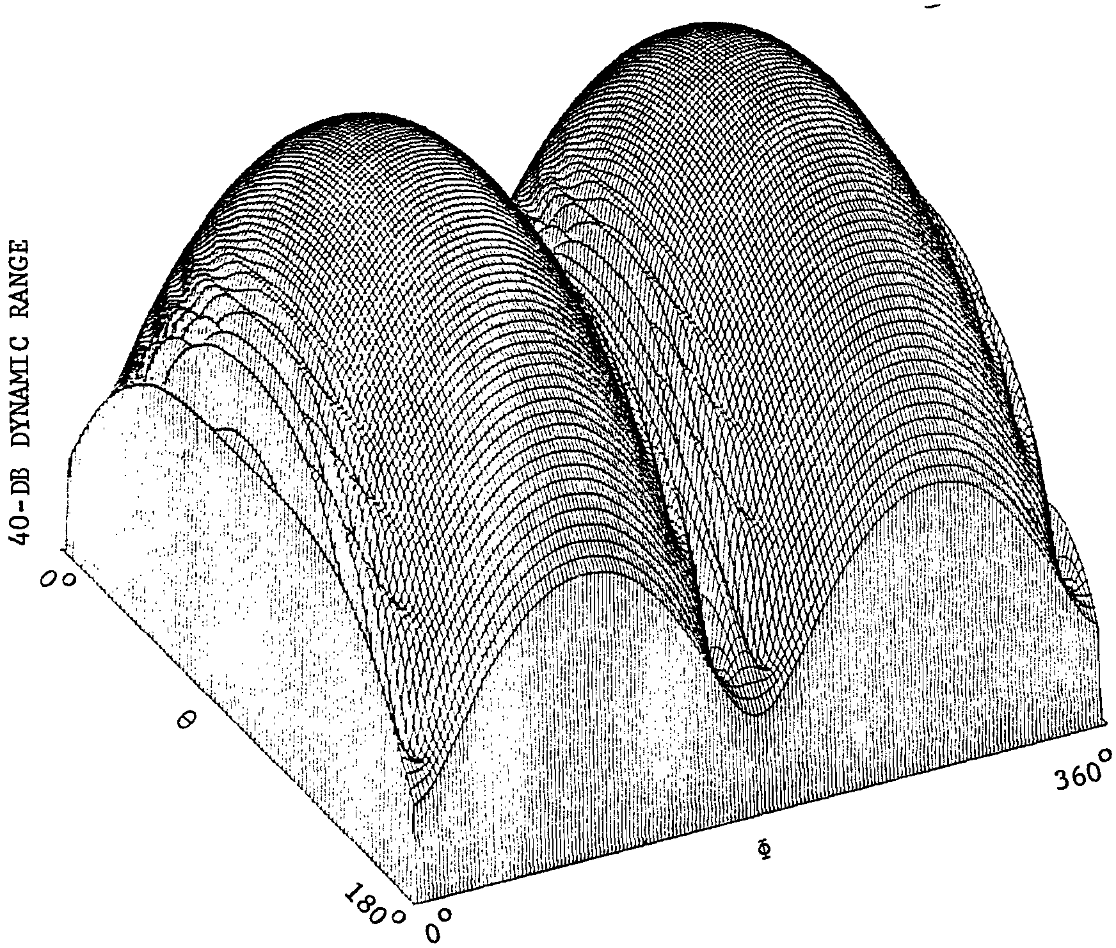


Figure 15. Calculated (scalar) radiation pattern for two symmetrically located elements having a 20-dB taper at 90° away from the peak on the SATRACK vehicle. The singles from the elements are added coherently at a frequency of 1.6 GHz.

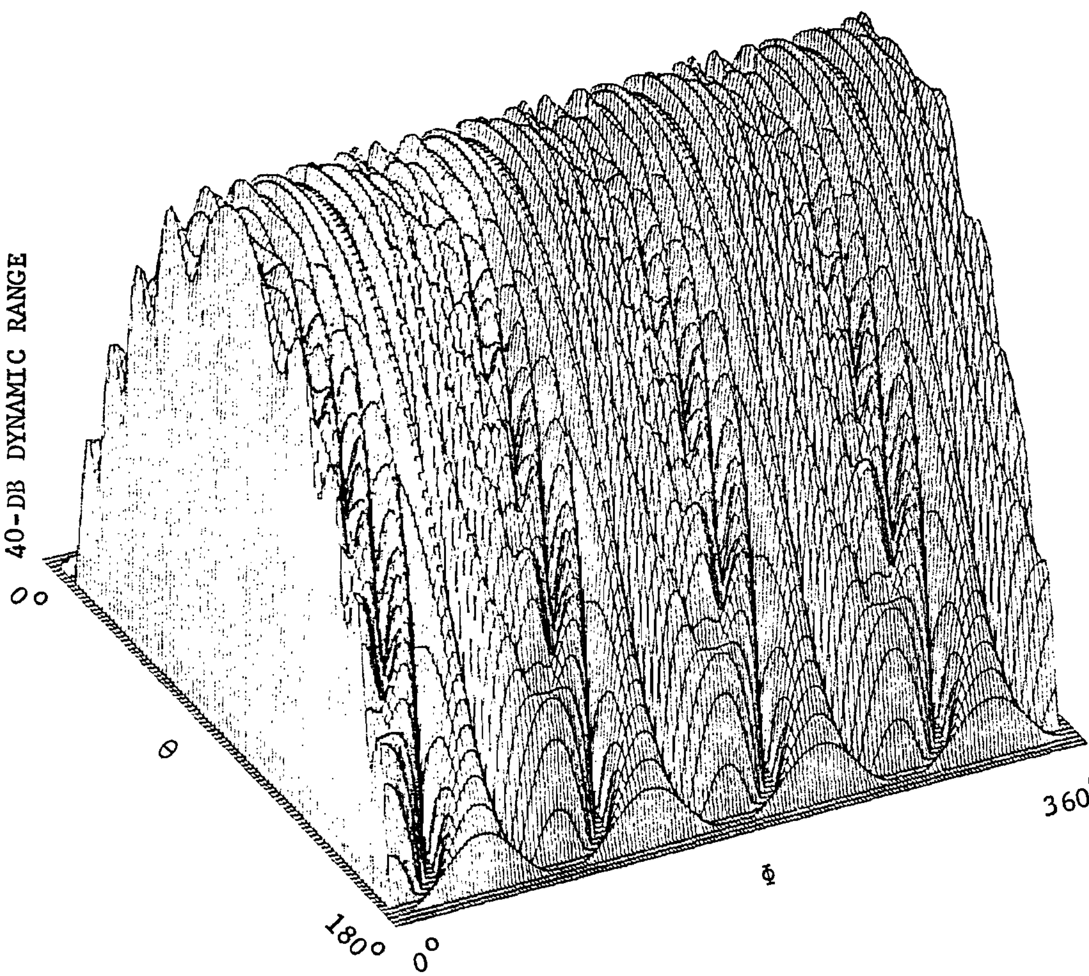


Figure 16. Calculated (scalar) radiation pattern for four symmetrically located elements having a 20-dB taper at 90° away from the peak on the SATRACK vehicle. The singles from the elements are added coherently at a frequency of 1.6 GHz.

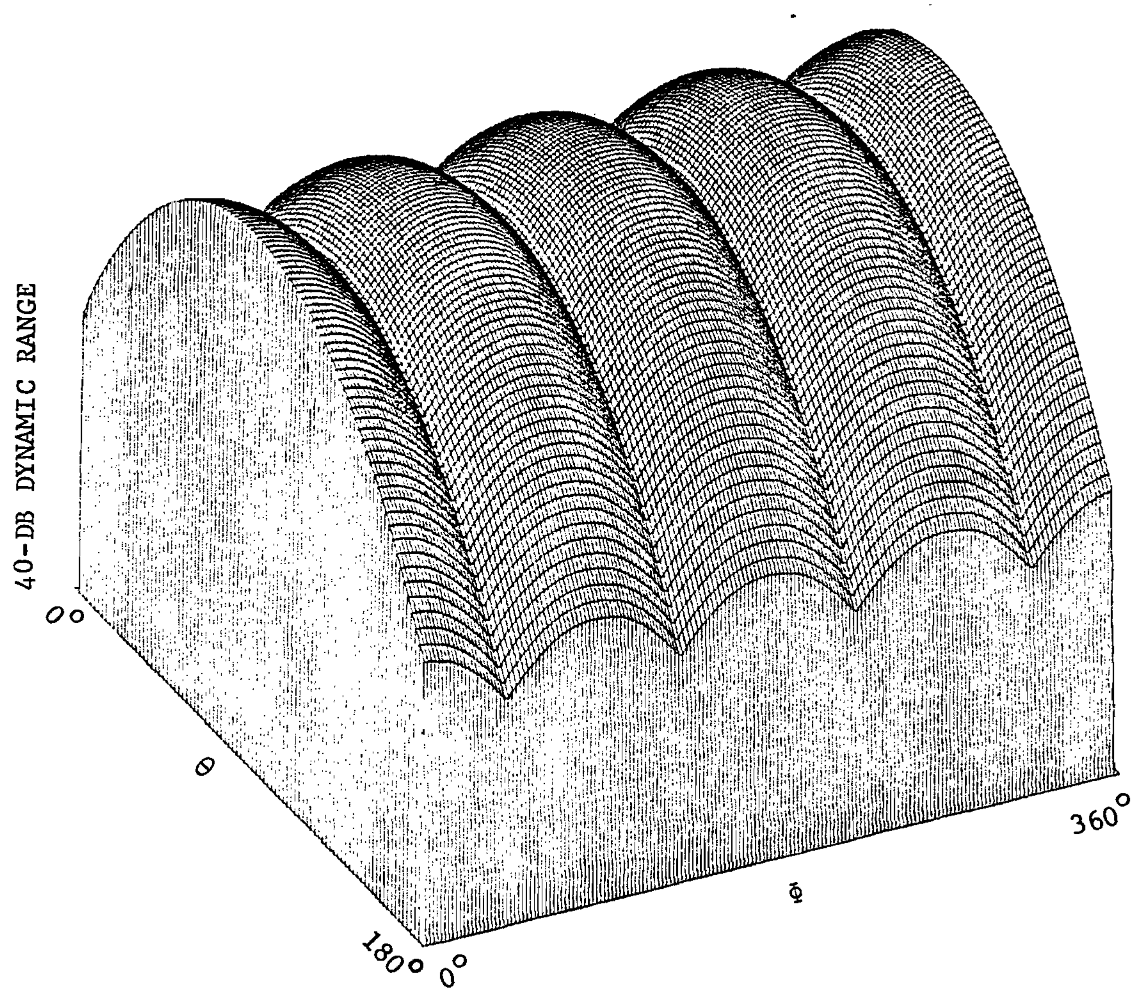


Figure 17. Calculated (scalar) radiation pattern for four symmetrically located elements having a 20-dB taper at 90° away from the peak on the SATRACK vehicle. The signals are combined in a time diversity fashion.

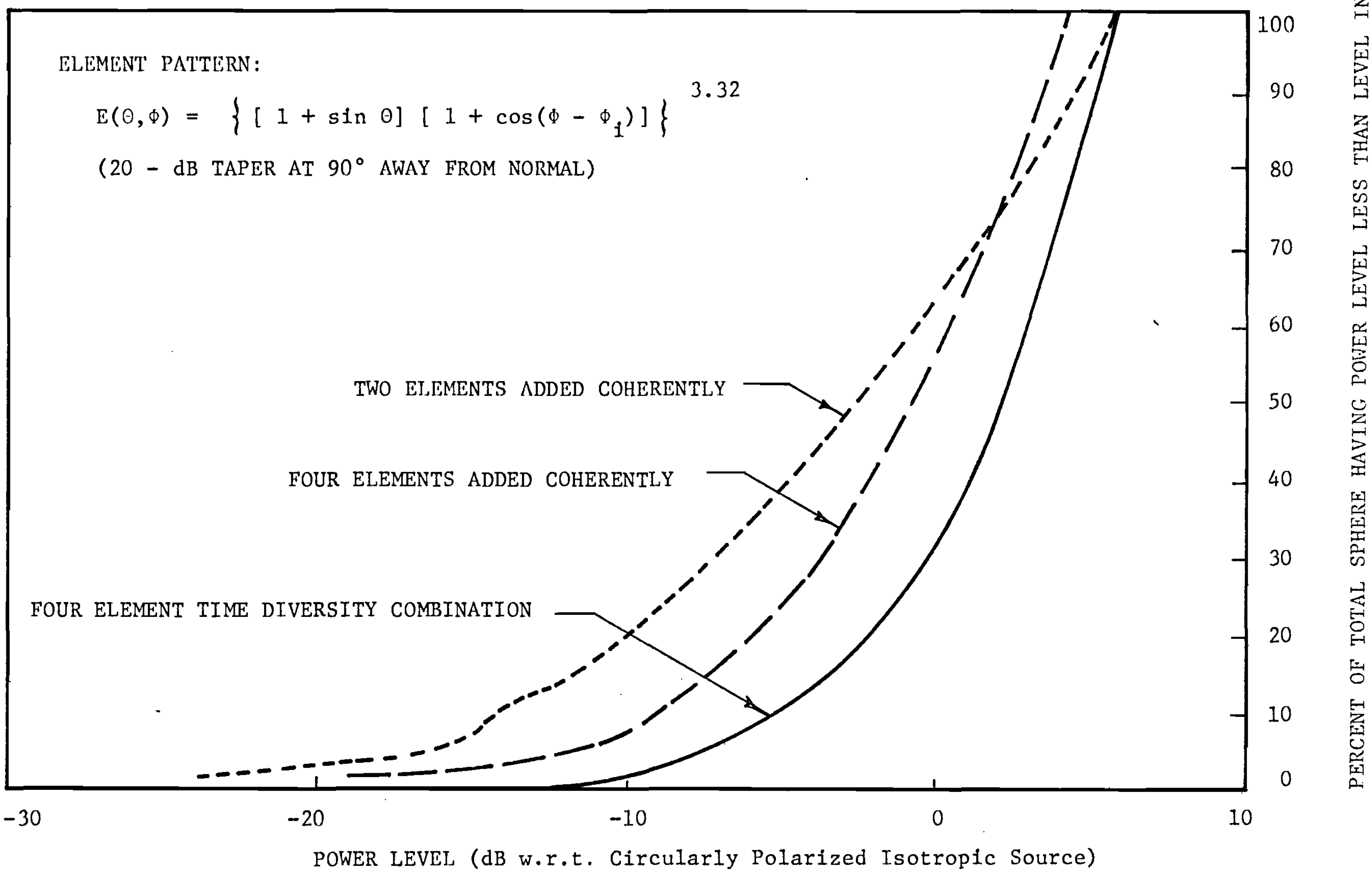


Figure 18. Calculated coverage levels over a complete sphere for two and four elements added coherently and for a four-element time diversity system.

performance while immersed in a dielectric observed as Messrs. R. B. Hester and E. E. Westerfield have requested a pair of high-temperature (200° F) omnidirectional elements at both 400 MHz and 1600 MHz for use in plume attenuation tests by 1 November 1974. Variable capacitors which are usable up into the lower microwave region have been ordered in an attempt to improve the gain of the 400 MHz plates and also to allow tuning of a pair of plates at 1600 MHz. Time diversity calculations will also be performed at 400 MHz during that period.

Respectfully submitted,

James W. Cofer, Jr.
SATRACK Project Director

Approved:

R. M. Goodman, Jr., Chief
Sensor Systems Division

JWC:jm

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

3 December 1974

Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland 20910

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task 2
(SATRACK Study)

Subject: Monthly Contract Technical Status Reports Nos. 7 and 8 covering the period 1 October through 30 November 1974

Gentlemen:

This includes the seventh and eighth Monthly Technical Status Reports under the referenced contract and covers the period 1 October through 30 November 1974.

During this report period, major emphasis was placed on element development. In addition some scalar pattern calculations were initiated during the latter portion of the period.

Further attention was given to the fabrication and testing of flat plate antennas (see Figures 7 and 9 of the September Monthly Status Report) for use at 400 MHz as this frequency appears to present the greatest problem from an element standpoint. In an effort to minimize the space requirement for the 400 MHz element, a circular element, similar to the one in Figure 1, was fabricated which had a ground plane (lower plate) diameter of six inches and a driven element (upper plate) of five inches. The element had a peak gain of -6 dBi LHCP and a LHCP radiation pattern as shown in Figure 2 (b). The coverage appears adequate; however, the peak gain is much too low. An attempt was made to increase the gain by enlarging the size of the lower plate which serves as a ground plane and thereby reflect energy which may be going into the rear sector back into the front sector. The effect on a given element of extending the ground plane was observed by placing the six-inch element of Figure 1 on an eight-inch square ground plane and attaching it to the lower plate with conducting tape. This new element still resonated at 400 GHz, had a peak gain of -3 dBi LHCP and a radiation pattern as shown in Figure 2 (a). This increase in gain is encouraging; consequently, it was decided to build four such elements (two for LMSC and two for Ed Westerfield's flame attenuation tests). Each element will have its own quadrature hybrid as a permament integral part (See Figure 3) so that each antenna will have to be tuned only once. Four such hybrids (Merrimac Model QHM-2-.375G) have been procured and the elements are currently being fabricated.

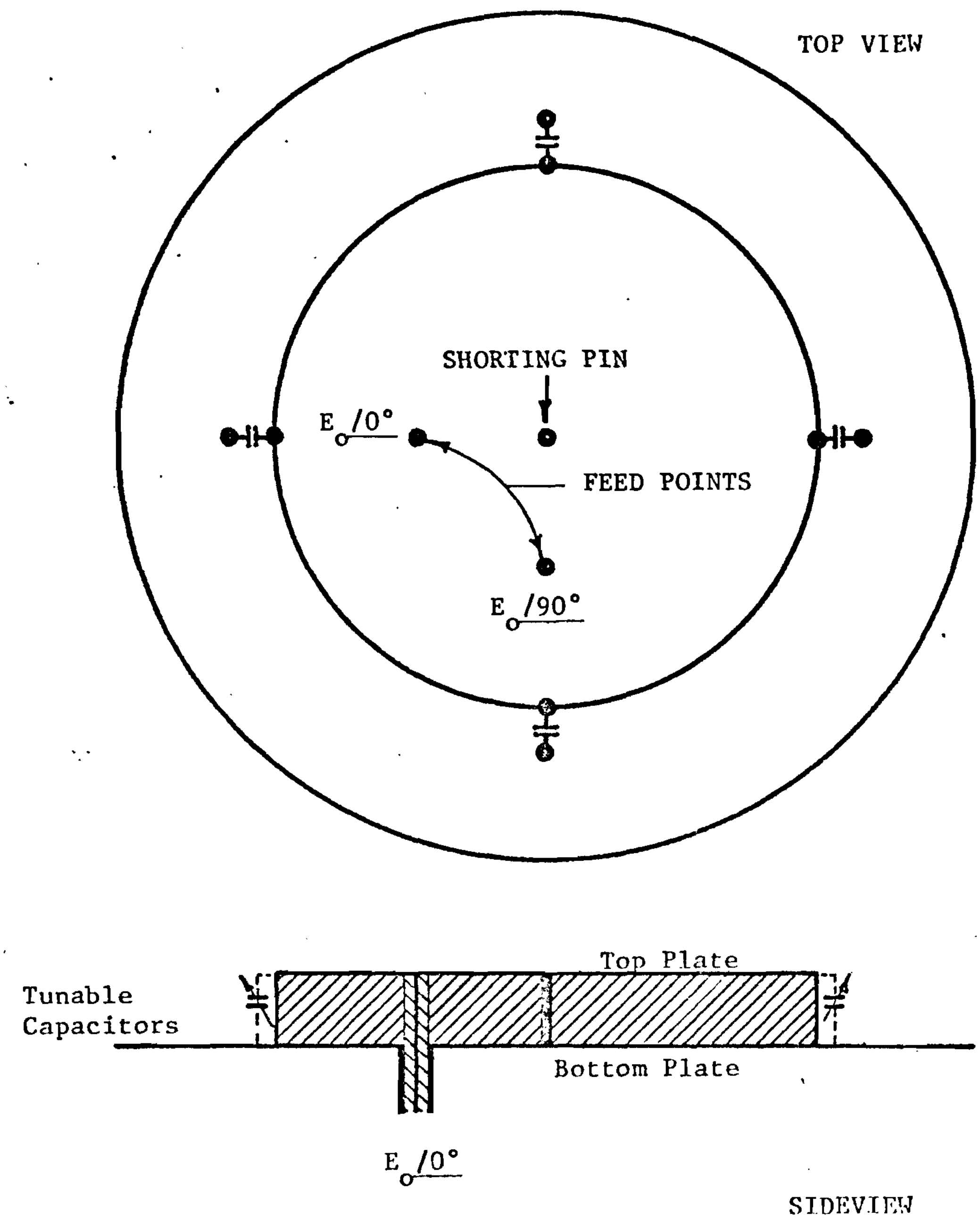
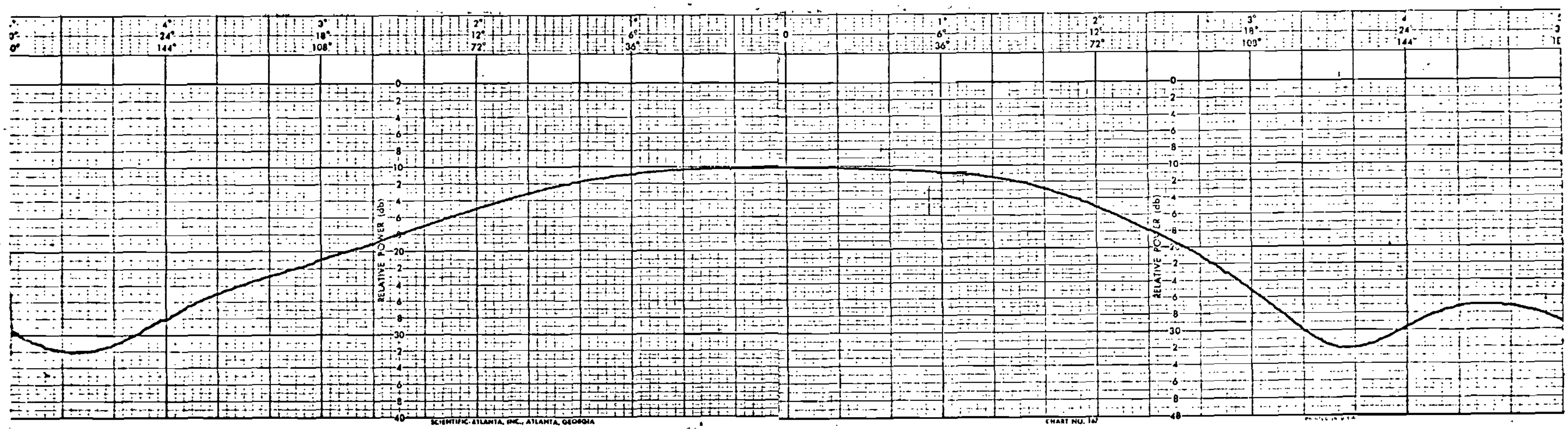


Figure 1. Simplified drawing of circularly polarized parallel plate antenna.

(a) Element attached to eight-inch square ground plane



(b) Element alone

Figure 2. Measured LHCP radiation patterns for a 400 MHz element consisting of a five-inch diameter plate located over a six-inch diamter lower plate. Pattern (b) is for the element alone while pattern (a) corresponds to the element attached to an eight-inch square ground plane.

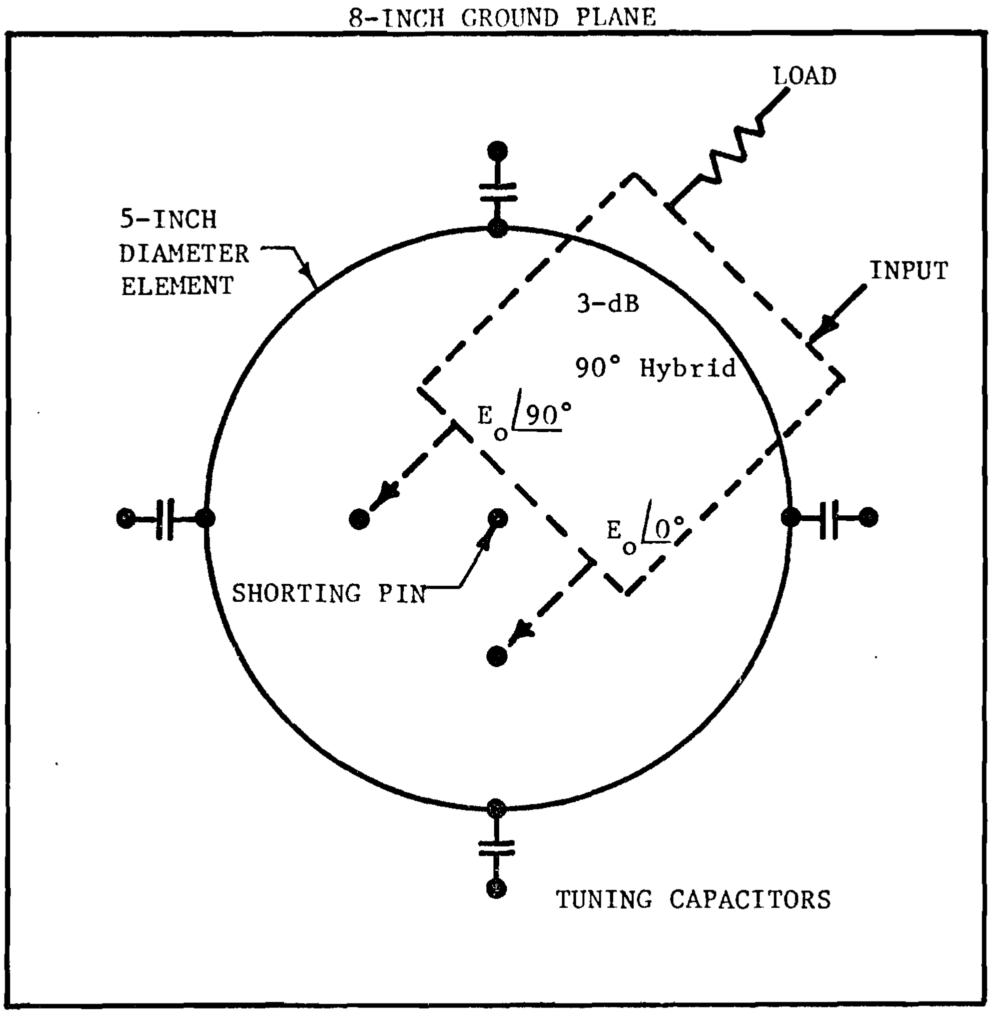


Figure 3. Top view of 400 MHz, circularly-polarized, flat-plate antenna. The five-inch driven element is separated from the ground plane by a one-quarter inch thick slab of dielectric (rexolite or polystyrene). Quadrature hybrid is fastened behind ground plane.

On 30 October 1974, Mr. J. W. Cofer of Georgia Tech visited LMSC facilities in Sunnyvale, California to discuss the on going anechoic chamber tests with Mr. Frank Butscher and his associates. At that time, Lockheed had tested various combinations of the quadrifilar helices which had been fabricated at Georgia Tech. These tests indicate that the helices actually had a RHCP gain higher than that of the LHCP component for which it was designed. Since LMSC and Georgia Tech are using the same polarization convention (IEEE) and the Georgia Tech helices are based on the design data contained in Bricker's* article, the cross polarization problem was not well understood at the time. Other elements have been built since that time which were identical in design to the previous ones (See Figure 1 of the September Monthly Status Report) except that a much smaller ground plane which touched the rear radial arms of the helices was used. This particular element, which incorporated a two-inch diameter circular ground plane and a 0.2 inch thick tube of teflon sheath around it, had a LHCP gain of + 5 dBi and principal plane radiation patterns as shown in Figures 4 (a) and (b). Three more such quadhelices will be fabricated and tested.

Also during this visit, it was learned that Lockheed was building circularly polarized cavity antennas for use at both 400 and 1575 MHz. The 400 MHz parallel plate antennas which were built by Georgia Tech and sent to Lockheed were claimed from the airlines by Lockheed's receiving department but never reached the antenna group. Another generation of these antennas (Figure 3) will be fabricated and sent to LMSC.

On 11 November 1974, Mr. J. W. Cofer attended a SATRACK meeting of APL and Navy personnel at APL facilities and gave a short briefing as to the status of antenna development. At that time, Lockheed was still pursuing the idea of circularly polarized elements. Also during this trip, copies of paper tapes containing radiation distribution information for the Georgia Tech quadhelices were obtained from Mr. R. L. Hickerson of APL. These tapes will be analyzed on the computer to determine the percent coverages for these elements.

Mr. Cofer visited APL again on 20 November 1974 to attend an antenna meeting chaired by Mr. Hickerson and attended by APL, contractors and Navy personnel. It was learned at this meeting that Lockheed has discontinued efforts to develop circularly polarized elements at either of the frequencies of interest. The basic problem seemed to be that a circular polarized cavity at 400 MHz would require about one square foot of "window" space and this is simply not available while the metal lip which attaches to the vehicle nose cover is in place. The Georgia Tech design (Figure 3) for this frequency requires an eight-inch ground plane, but the radiating element is only five inches in diameter; consequently, this element could possibly be mounted above the metal lip. Lockheed personnel indicated at this meeting that they would continue to test Georgia Tech antennas but strictly on a non-interference basis with their linear element development effort.

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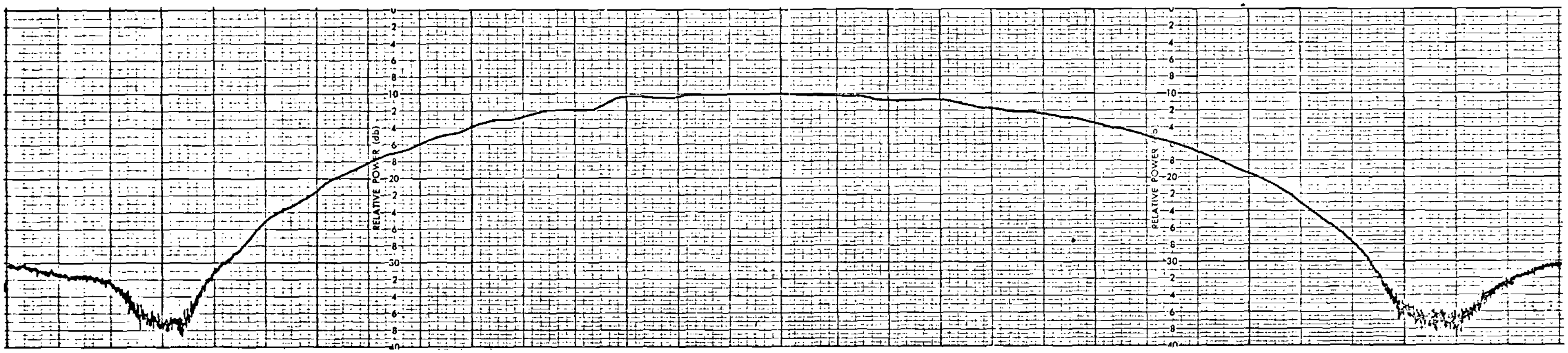
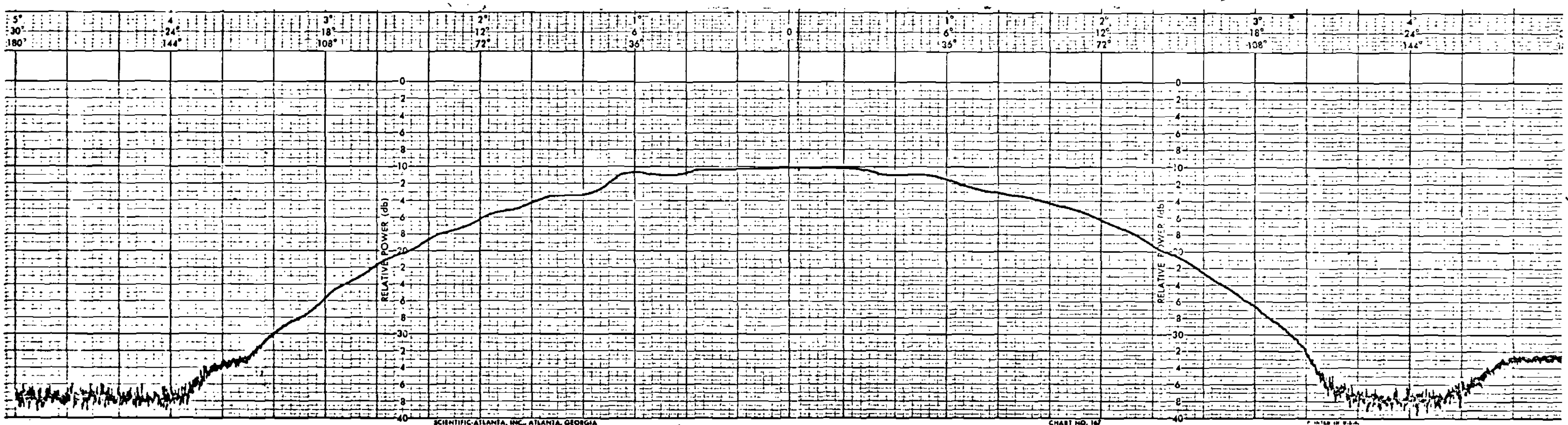
*Bricker, R.W. and Rickert, H. H., "An S-Band Resonant Quadrifilar Antenna for Satellite Communication," Digest of the 1974 International IEEE/AP-S Symposium held at Georgia Institute of Technology, Atlanta, Georgia June 10-12, 1974, pp. 78-82.



(a) Plane A



(b) Plane B (Orthogonal to Plane A)

Figure 4. Measured LHCP radiation patterns in two orthogonal planes for a 1550 MHz quadrifilar helix soldered to a two-inch diameter ground plane and enclosed in a teflon sheath.

During this same visit, Messrs. Cofer and Hickerson discussed the type of amplitude and phase variations which might be expected from a two-element array. As a result of these discussions, it was agreed that Georgia Tech would calculate scalar radiation patterns in constant-θ (see Figure 5) cones about the vehicle axis. These patterns may be found from simple array theory to be

$$E(\theta,\phi) = G_1(\theta,\phi)\, e^{-j\psi_1(\theta,\phi)}\, e^{j\gamma} + G_2(\theta,\phi)\, e^{-j\psi_2(\theta,\phi)}\, e^{-j\gamma} \qquad (1)$$

where γ = ka sinθ cos ϕ,

G_i = voltage amplitude pattern of element i,

ϕ_i = element ϕ-pointing directions

ψ_i = phase pattern of element i

a = vehicle radius

These equations may be reduced to the form

$$E = \left(G_1 \cos\alpha + G_2 \cos\beta\right) + j\left(G_1 \sin\alpha - G_2 \sin\beta\right) \qquad (2)$$

where G_1 and G_2 are cardioids with variable directivities and given by

$$G_i = \left[1 + \sin\theta \cos(\phi - \phi_i)\right]^\rho$$

$$\alpha = \gamma - \psi_1(\theta,\phi)$$

$$\beta = \gamma + \psi_2(\theta,\phi)$$

Several patterns were calculated in the roll plane (θ = 90°) at a frequency of 400 MHz. Power and phase plots for five different arrays are shown in Figures 6 through 15. It may be noted from these Figures that complete cancellation occurs at only two points (ϕ = 90°, and 270°) and that is when $\psi_1 - \psi_2$ = 180° (Figure 8). The effect of letting ψ_1 and ψ_2 differ by 0°, 45°, and 90° is shown in Figures 6, 10, and 12, respectively, to cause a slight angular shift in the location of the maxima and minima. The effect of letting Element #2 point along ϕ= 150° instead of 180° is shown in Figure 14 to be a distorting of the pattern and a slight rearranging of the nulls. The element squinting does not appear to offer any potential for null filling.

An examination of the phase patterns reveals that the phase variations are actually quite smooth and probably just due to the geometric variation of the phase center except when going through a point of total cancellation (see Figures 8 and 9). The instantaneous phase jumps for the other cases are always from +180° to -180° (or vice versa) which is due to the fact that the computer's inverse tangent function is limited to this range.

During the month of December, Equation (2) will be evaluated for several other cases including

(1) functional forms for ψ_1 and ψ_2 instead of constants,

(2) increased cardioid directivity ($\rho > 1$), and

(3) frequency = 1575 MHz

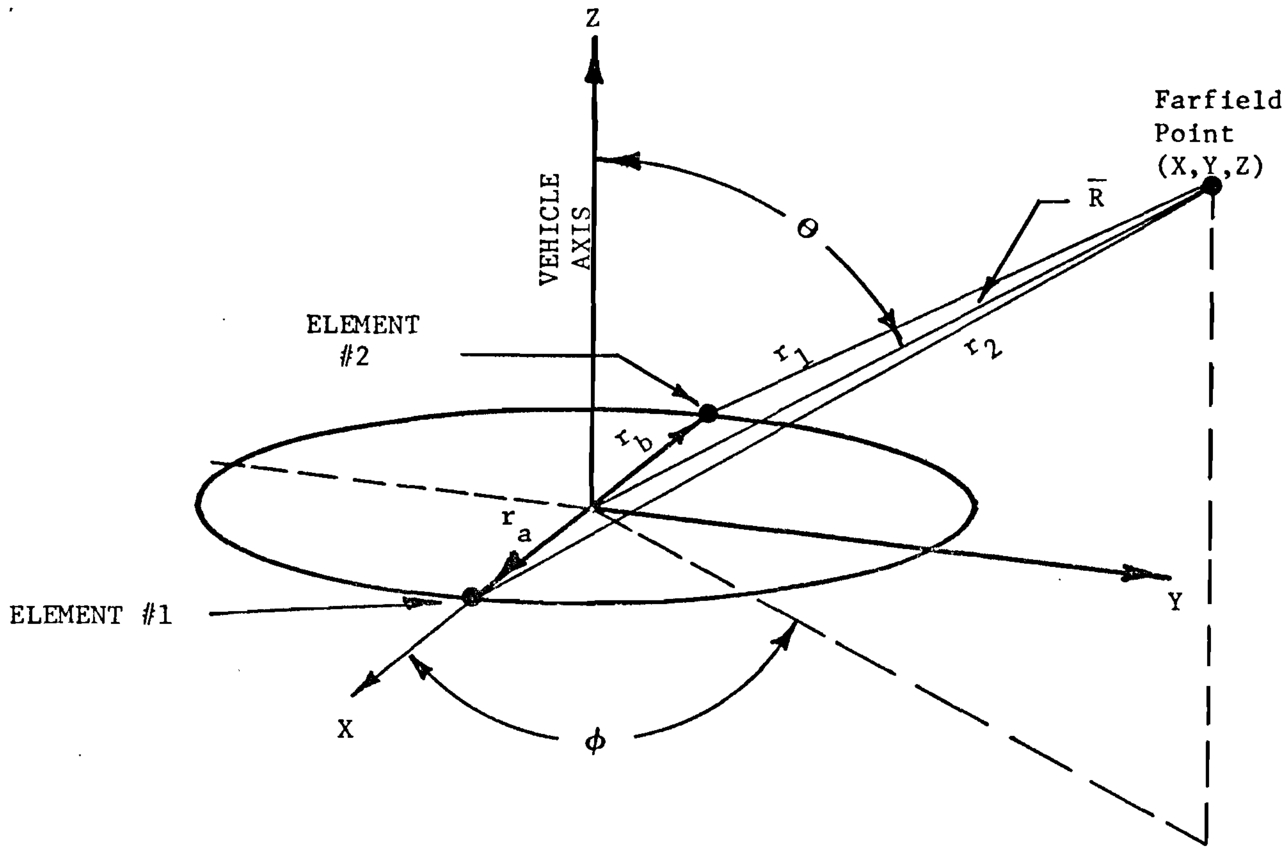


Figure 5. Coordinate system used for calculation of phase and amplitude patterns.

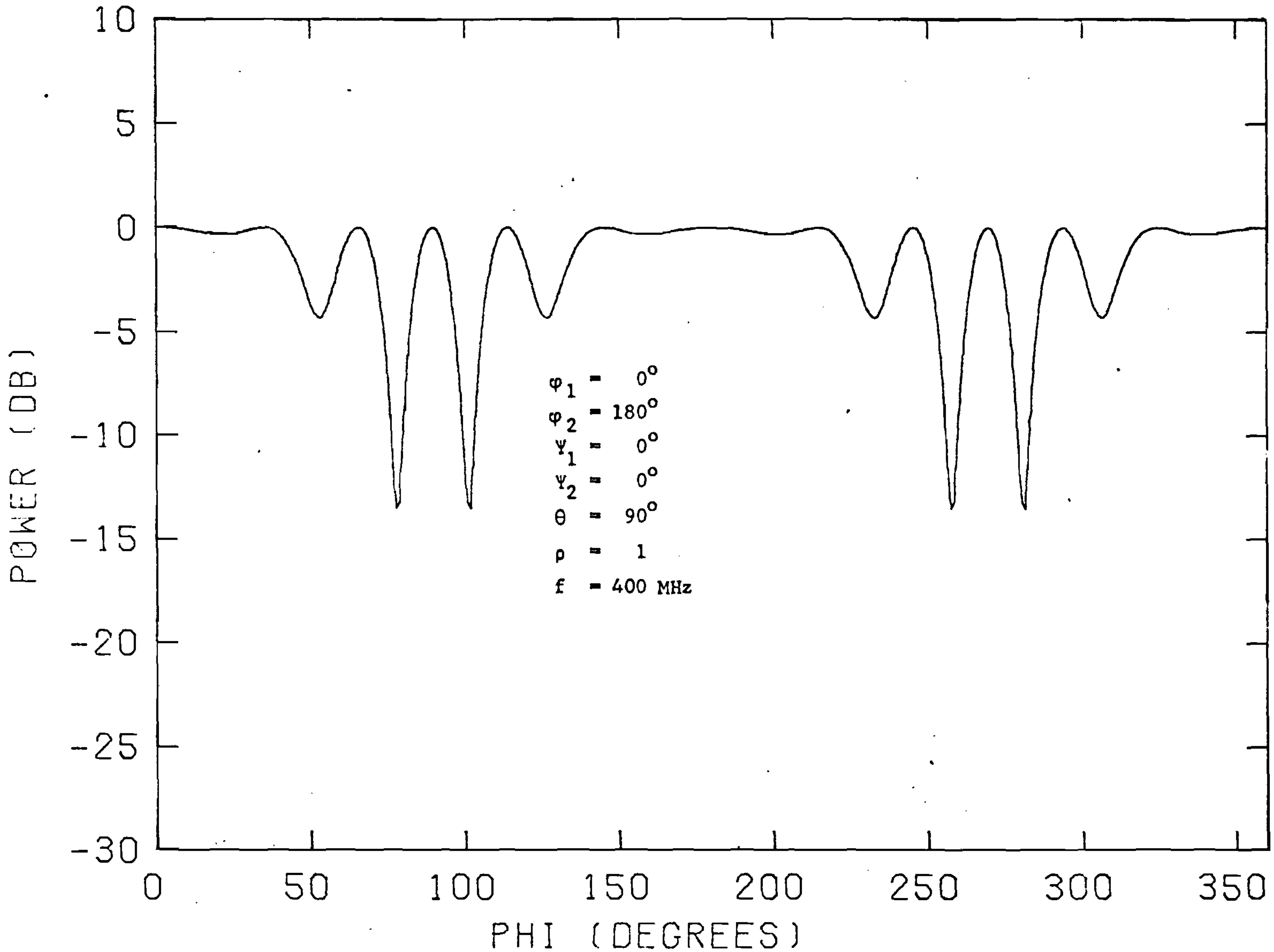


Figure 6. Calculated (scalar) farfield radiation pattern for a two-element array having the parameters designated.

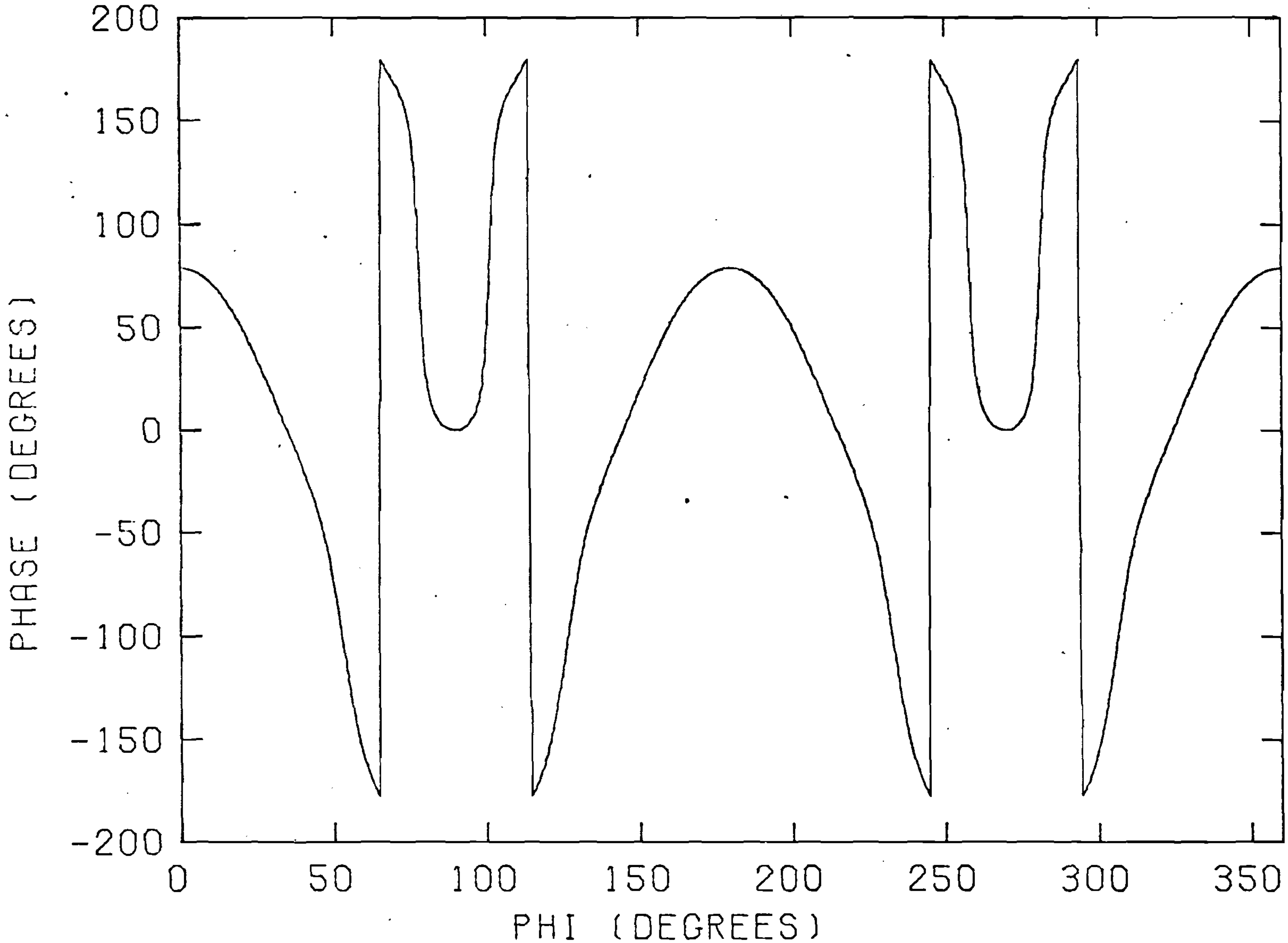


Figure 7. Calculated (scalar) farfield phase for a two-element array having the parameters designated in Figure 6.

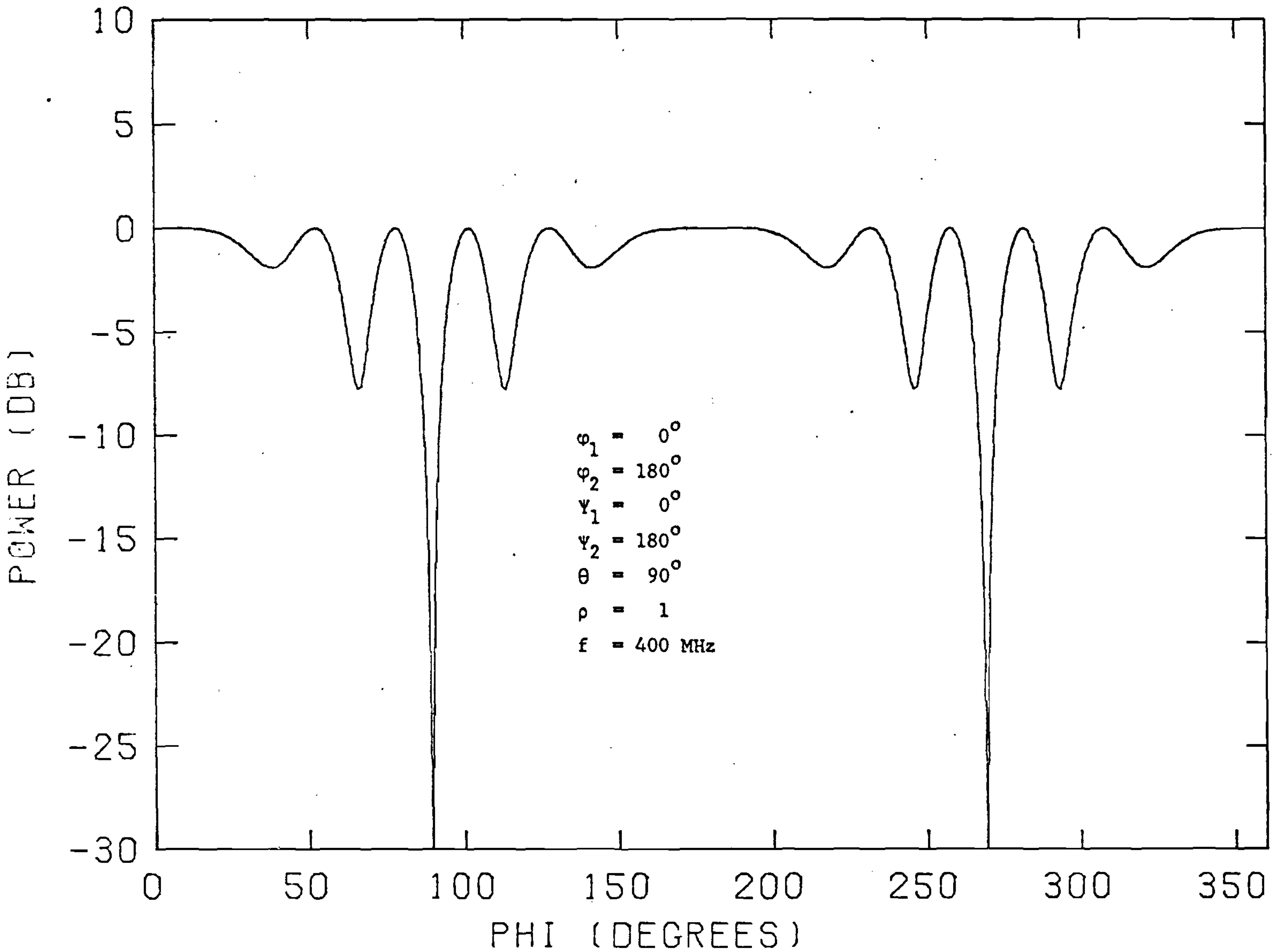


Figure 8. Calculated (scalar) farfield radiation pattern for a two-element array having the parameters designated.

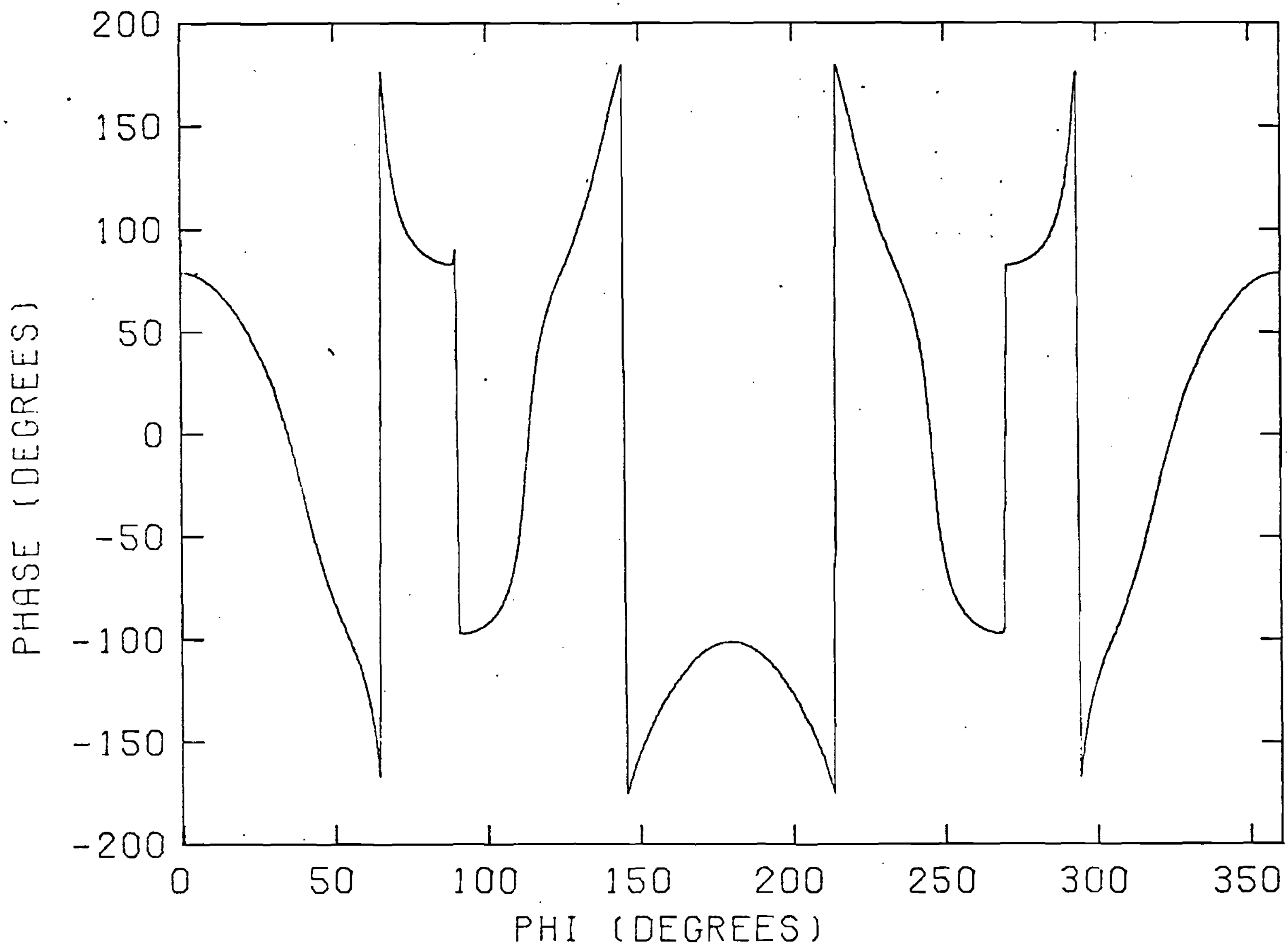


Figure 9. Calculated (scalar) farfield phase for a two-element array having the parameters designated in Figure 8.

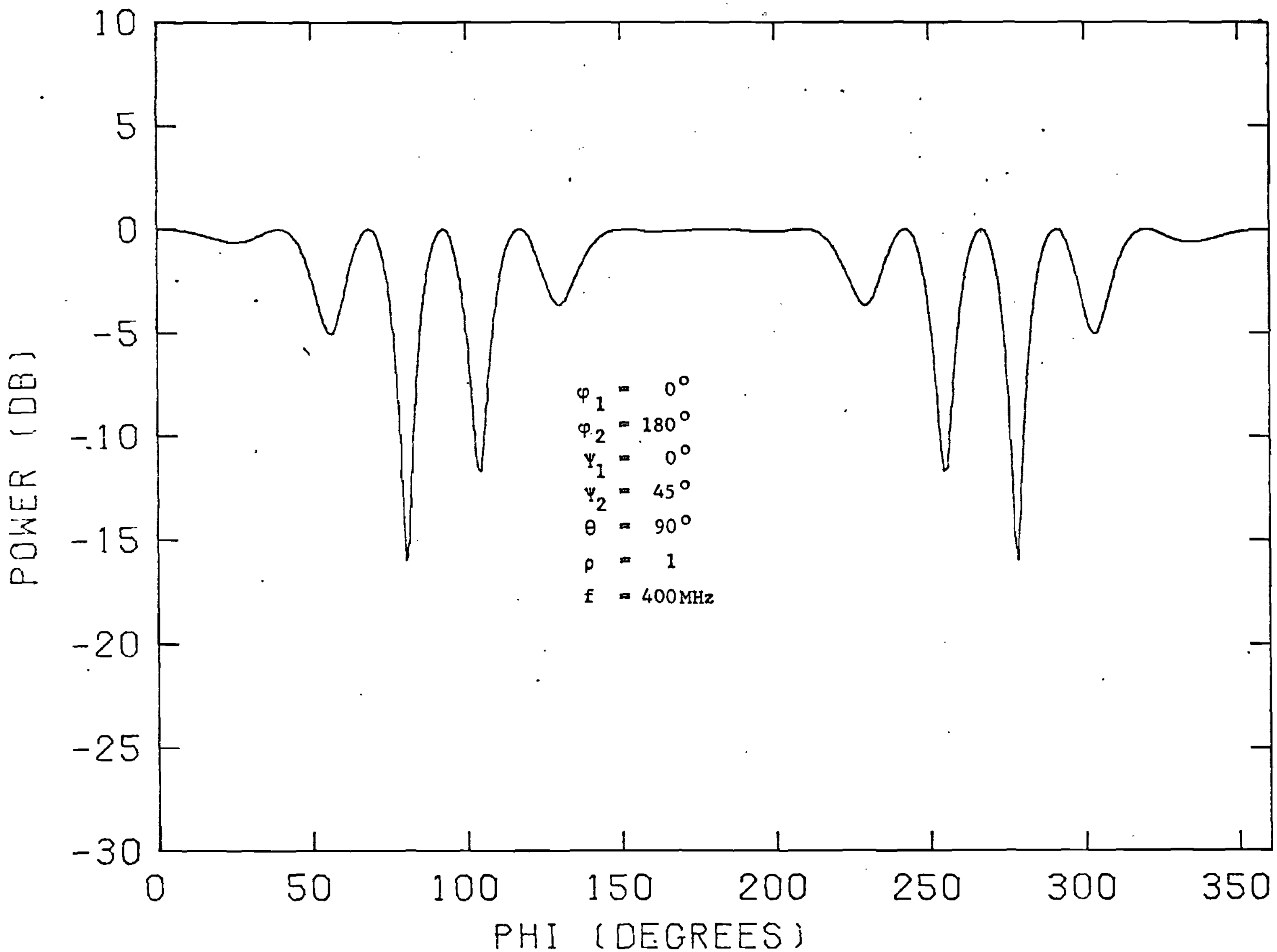


Figure 10. Calculated (scalar) farfield pattern for a two-element array having the parameters designated.

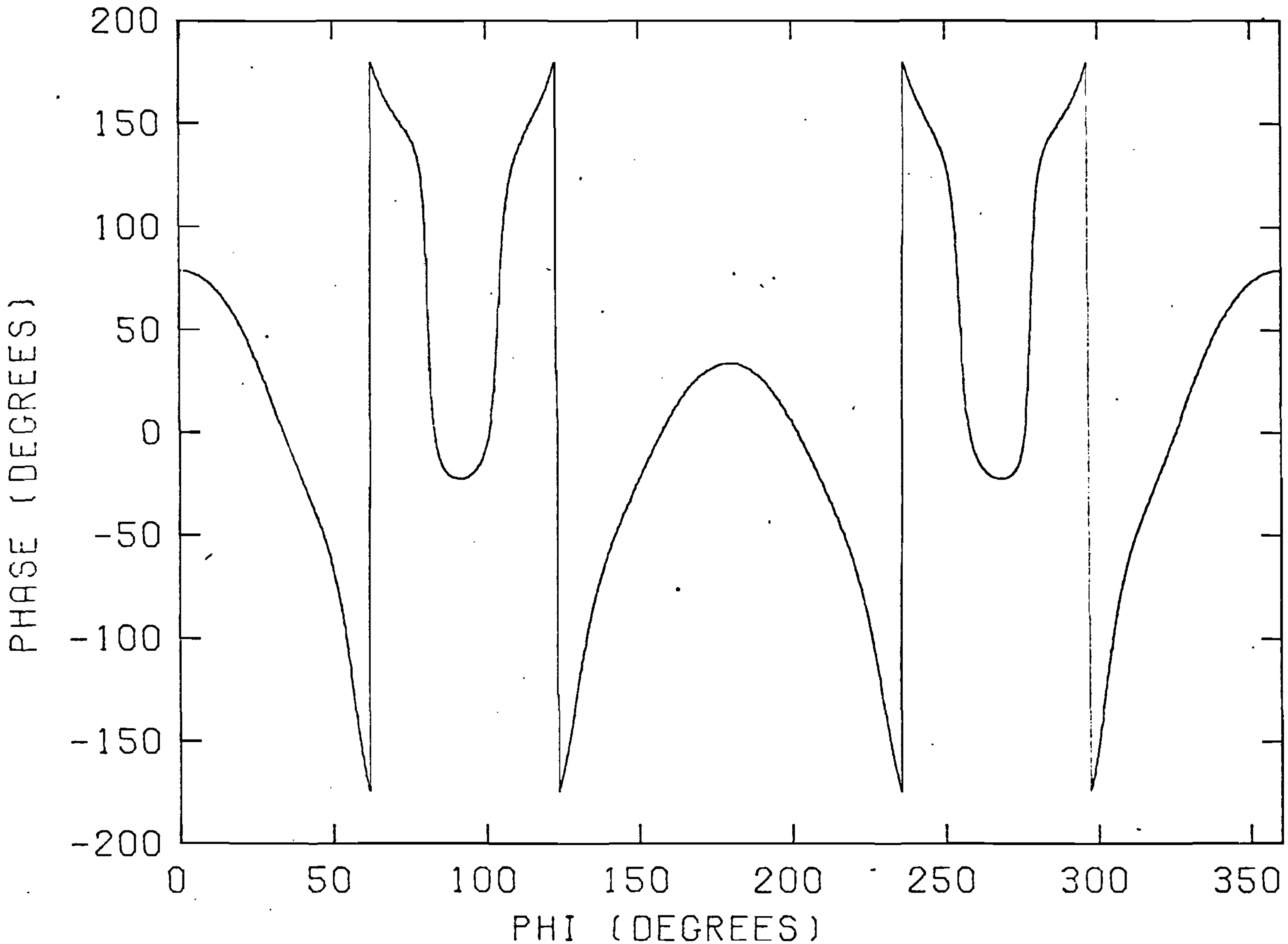


Figure 11. Calculated (scalar) farfield phase for a two-element array having the parameters designated in Figure 10.

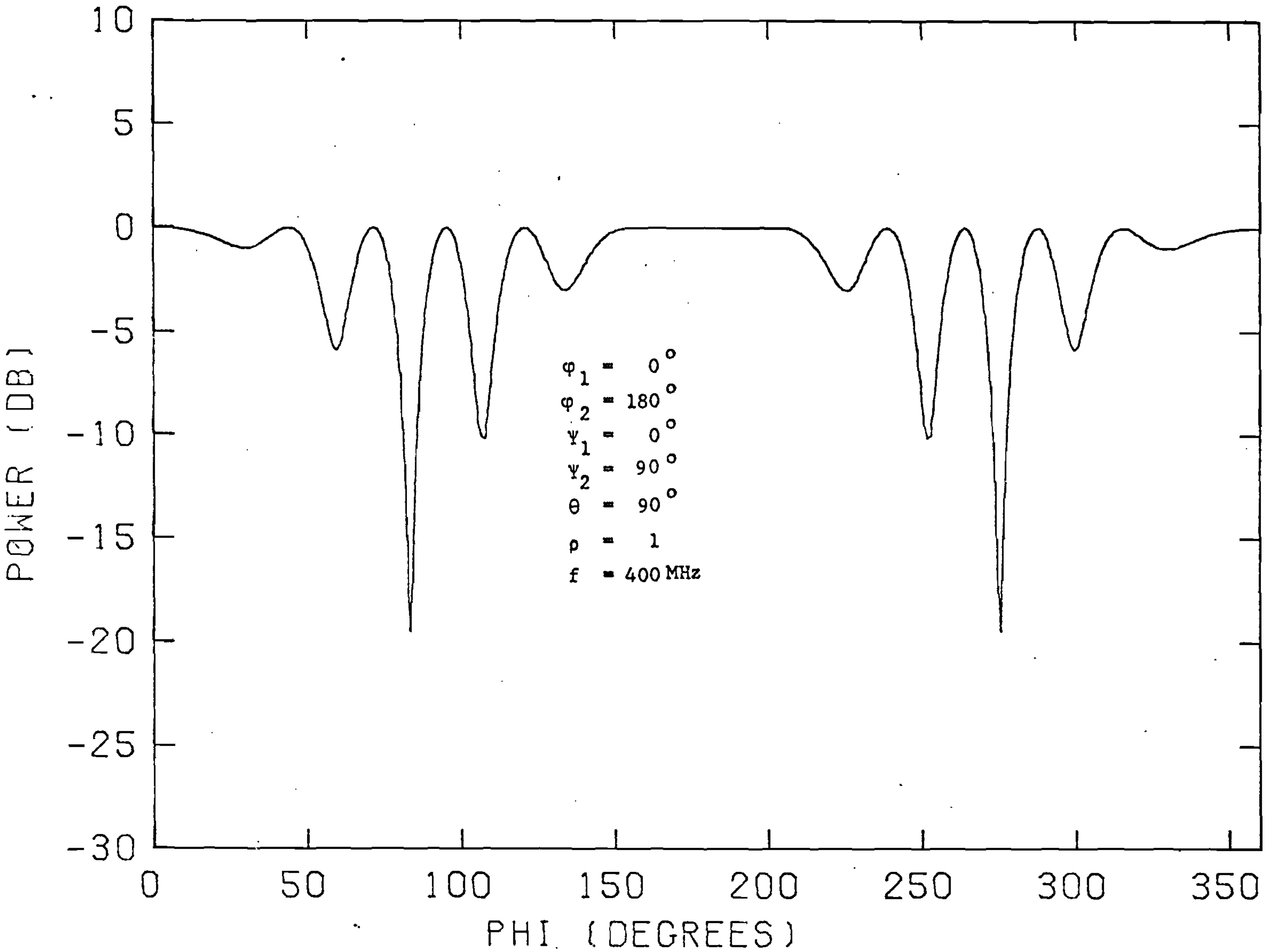


Figure 12. Calculated (scalar) farfield radiation pattern for a two-element array having the parameters designated.

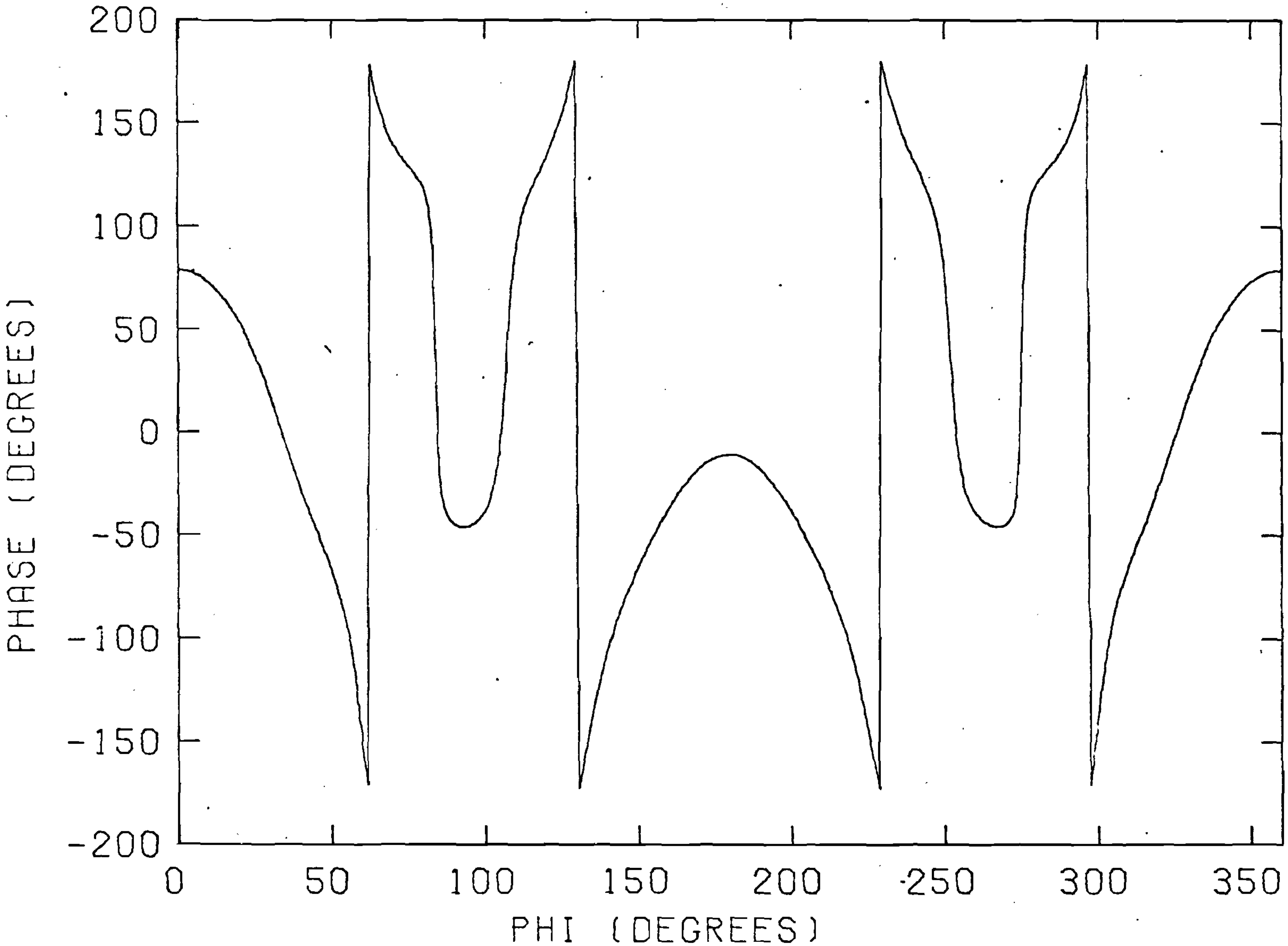


Figure 13. Calculated (scalar) farfield phase for a two-element array having the parameters designated in Figure 12.

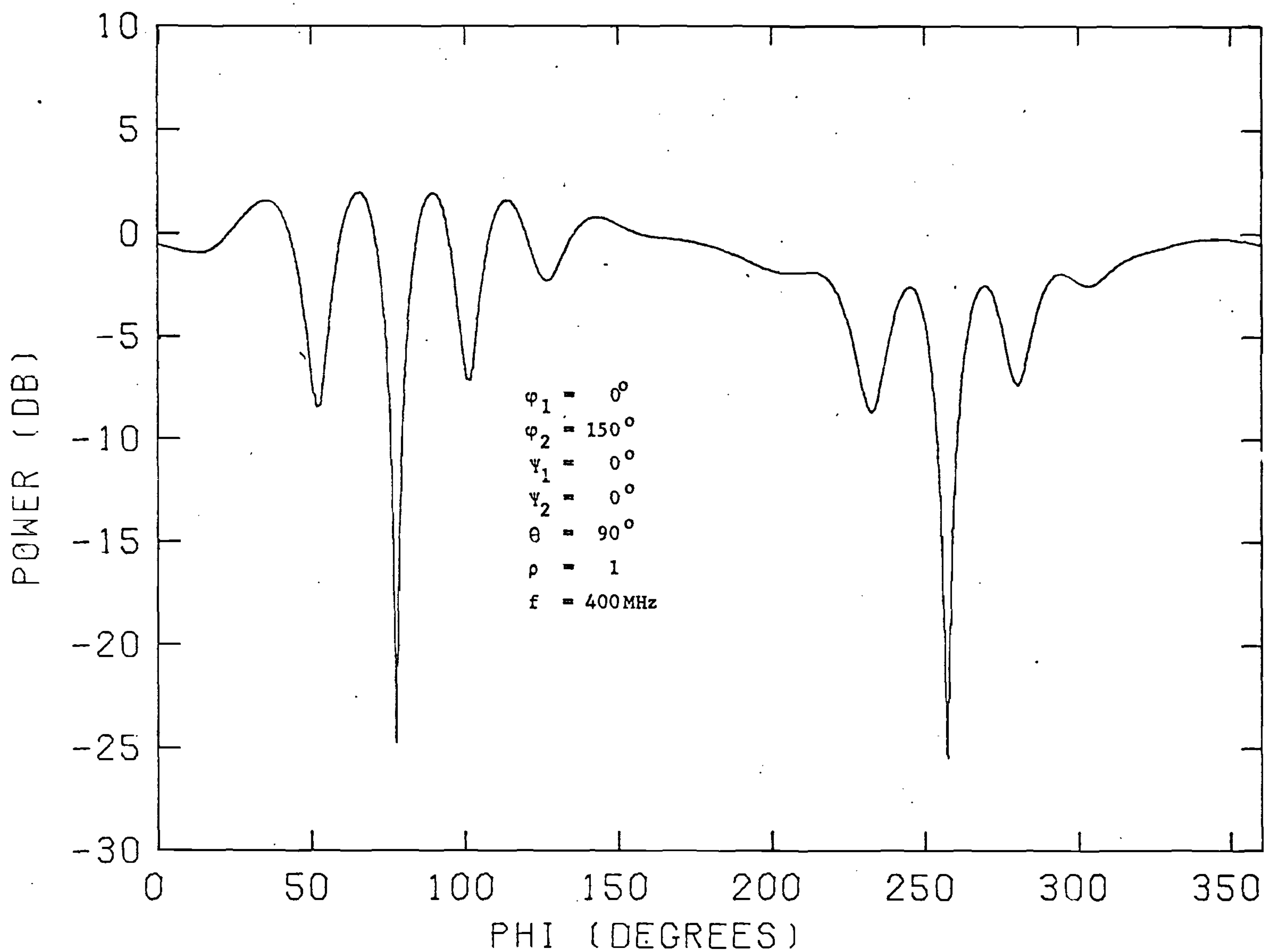


Figure 14. Calculated (scalar) farfield radiation pattern for a two-element array having the parameters designated.

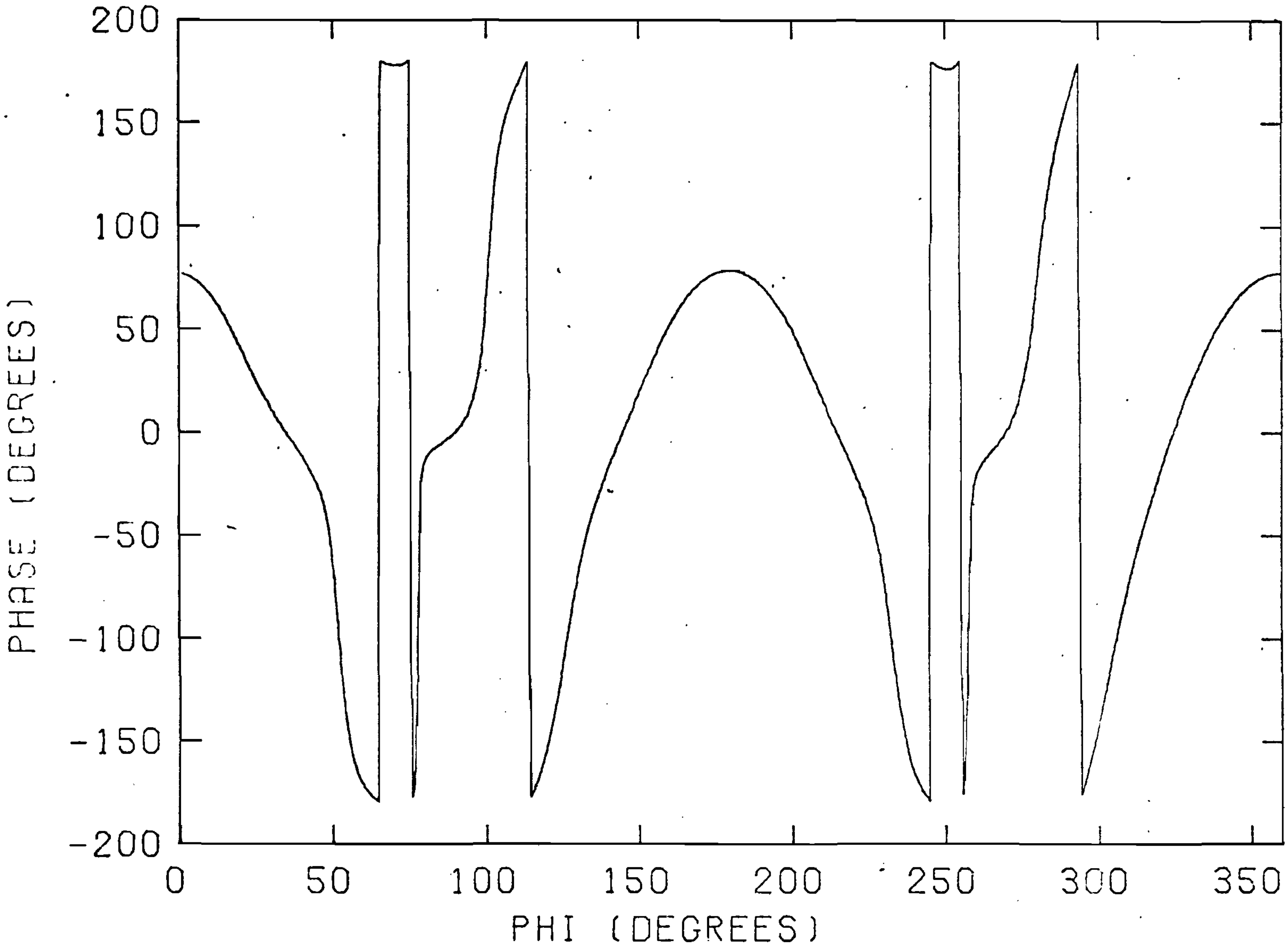


Figure 15. Calculated (scalar) farfield phase for a two-element array having the parameters designated in Figure 14.

The paper tapes containing the radiation distribution information for the Georgia Tech quadhelices were obtained during the November 11 meeting at APL. These tapes have been read into the computer for coverage calculations; however, the data contains a large number of "spikes" which affect the calculations. These spikes will have to be edited out before meaningful directivity and coverage numbers can be found.

As of 1 December 1974, $14,210.24 of the first increment ($25,000) of the total contract funds ($49,972) have been expended leaving a total unexpended balance of $10,789.76. At this point in the program, it is felt that these funds in addition to the second increment ($24,972) will be adequate to accomplish the program's objectives.

During the forthcoming report period, efforts will be made to complete the fabrication and testing of four quadrifilar helices for 1575 MHz and four parallel plate antennas for 400 MHz. Two of each antenna type will be sent to LMSC for testing and two of each will be sent to Mr. E. E. Westerfield of APL for flame attenuation tests. The scalar calculation of constant - θ patterns will also be continued.

Respectfully submitted,

James W. Cofer, Jr.
SATRACK Project Director

JWC:jm

A-1617-100

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

1 May 1975

Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland 20910

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task 2
(SATRACK Study)

Subject: Monthly Contract Technical Status Reports Nos. 12 and 13 covering the period 1 March 1975 through 30 April 1975

Gentlemen:

This includes the twelfth and thirteenth Monthly Technical Status Reports under the referenced contract and covers the period 1 March 1974 through 30 April 1975.

In early April 1975, Mr. Charles McGrath of APL called Mr. J. W. Cofer of Georgia Tech to request that specifications be written to describe the performance of two antennas which will be used as ground based links to the vehicle. At that time, Mr. McGrath relayed such information as frequencies, bandwidth, polarization, power handling, and beam shape. He suggested that the quadrifilar helix be recommended to the contractor who will eventually design and fabricate the antennas.

Mr. R. B. Hester of APL called Mr. R. M. Goodman of Georgia Tech on 16 April 1975 to further discuss this task. He indicated that APL prefers that Georgia Tech personnel apply the required effort to the generation of the subject specifications and that all work on the project Final Report should be terminated. This deletion of the Final Report will require a modification to the contractual Statement of Work; consequently, Georgia Tech will proceed under the assumption that this modification will be initiated by APL in the near future.

During the month of April, Mr. J. W. Cofer and Mr. H. L. Bassett, a staff member who has directed projects in the area of missile and spacecraft antennas, have compiled a set of specifications which will parallel APL's system requirements while remaining within the realm of known physical antenna systems. These specifications are currently in rough draft form with efforts still remaining in the areas of: (1) the percentage of the hemisphere over which the radiation must be kept above the desired level and (2) determining a physically feasible null depth along the horizon. These efforts will be completed during the first week of May, and the final specifications will be submitted to Mr. McGrath immediately thereafter.

As of 1 April 1975, $46,481.81 of the total contract funds ($49,957.00) have been expended leaving an available balance of $3,475.19. Although budgetary information for the month of April is not yet available it is estimated that approximately $400.00 was expended leaving an unexpended balance of approximately $3,100.00.

Respectfully submitted,

James W. Cofer
SATRACK Project Director

JWC:jm

Approved:

E. K. Reedy, Head
Systems Technology Branch

cc: R. B. Hester
R. M. Goodman, Jr.

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

2 June 1975

Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland 20910

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task 2
(SATRACK Study)

Subject: Monthly Contract Technical Status Report No. 14 covering the period 1 May 1975 through 31 May 1975

Gentlemen:

This includes the fourteenth Monthly Technical Status Report under the referenced contract and covers the period 1 May 1975 through 31 May 1975.

During this report period, the performance specifications for two ground-based antennas for the SATRACK program were completed and mailed on 12 May 1975. Copies were forwarded to the Program Manager, Mr. R. B. Hester, the Project Monitor, Dr. C. C. Kilgus, and the user, Mr. Charles McGrath.

As of 1 May 1975, \$47,388.91 of the total contract funds (\$49,957.00) have been expended leaving a total unexpended balance of \$2,568,09. Although budgetary information for the month of May is not yet available, it is anticipated that approximately \$1,000.00 was expended in the course of completing the specifications leaving an unexpended balance of approximately \$1,550.00. Since no designated tasks remain under this contract, these funds are available for Georgia Tech to provide support to APL in their SATRACK mission.

Respectfully submitted,

James W. Cofer
SATRACK Project Director

Approved:

E. K. Reedy, Head
Systems Technology Branch

cc: R. B. Hester, R. M. Goodman, Jr.

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

1 July 1975

Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland 20910

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task 2
(SATRACK) Study

Subject: Monthly Contract Technical Status Report No. 15 covering the period 1 June 1975 through 30 June 1975

Gentlemen:

This represents the fifteenth Monthly Technical Status Report under the referenced contract and covers the period 1 June 1975 through 30 June 1975.

During the month of June, Mr. Charles McGrath of APL called to say that the SATRACK ground-based antenna specifications had been received and reviewed and that he would like to make a number of changes. These changes were incorporated into the specification and the resulting document was forwarded to Mr. McGrath, and copies were mailed to Mr. R. B. Hester and Dr. C. C. Kilgus.

As of 1 June 1975, $48,145.08 of the total contract funds ($49,957.00) have been expended leaving a total unexpended balance of $1,811.92. Although budgetary information for the month of June is not yet available, it is anticipated that approximately $400.00 was expended in the course of modifying the specifications leaving an unexpended balance of approximately $1,400.00. Since no designated tasks remain under this contract, these funds are available for Georgia Tech to provide support to APL in their SATRACK mission.

Respectfully submitted,

James W. Cofer
SATRACK Project Director

Approved:

R. M. Goodman, Jr.
Chief, Sensor Systems Division

cc: R. B. Hester

A - 1617 - 100

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

1 August 1975

Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland 20910

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task 2
(SATRACK) Study

Subject: Monthly Contract Technical Status Report No. 16 covering the period 1 July 1975 through 31 July 1975

Gentlemen:

This represents the sixteenth Monthly Technical Status Report under the referenced contract and covers the period 1 July 1975 through 31 July 1975.

During this report period, project efforts were directed toward further revision of the specifications for two ground based antennas and also a budgetary estimate for fabricating two such antennas.

Mr. Charles McGrath of APL called in early July to say that the latest revised version of the specifications had not been received. These specifications had been mailed in mid-June; therefore second copies were mailed to Messrs. Hester, McGrath, and Kilgus in July. Mr. McGrath called a few days later to say that both mailings had been received and, he felt that some slight modifications in wording were appropriate. It was agreed by phone that Mr. McGrath would make these changes to his copy and have it re-typed without another formal transmission through the mail.

Also during this report period, Georgia Tech personnel submitted an unsolicited proposal to APL to design, fabricate, and test the two ground-based antennas. It should be stressed that no contract funds were expended in the preparation of this proposal. Mr. Harold Bassett, who has developed models of the proposed antenna type (helices) both for the current SATRACK contract and for a NASA program, will serve as Project Director of the proposed work.

As of 1 July 1975, $48,345.76 of the total contracts funds ($49,957.00) have been expended leaving a total unexpended balance of

$1,611.24. Although budgetary information for the month of July is not yet available, it is anticipated that approximately $200.00 was expended in the course of modifying the specifications leaving an unexpended balance of approximately $1,400.00. Since no designated tasks remain under this contract, these funds are available for Georgia Tech to provide support to APL in their SATRACK mission.

Respectfully submitted,

James W. Cofer
SATRACK Project Director

JWC:jm

Approved:

E. K. Reedy
Head, Systems Technology Branch

cc: R. B. Hester
R. M. Goodman, Jr.

A-1617-100

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

2 September 1975

Applied Physics Laboratory
The Johns Hopkins University
Silver Spring, Maryland 20910

Attention: Dr. C. C. Kilgus

Reference: APL Subcontract No. 600128
Amendment No. 1, Task 2
(SATRACK) Study

Subject: Monthly Contract Technical Status Report No. 17 covering the period 1 August 1975 through 31 August 1975

Gentlemen:

This represents the seventeenth and final Monthly Technical Status Report under the referenced contract and covers the period 1 August 1975 through 31 August 1975.

During this report period, several wording modifications were made to the specifications for two ground based antennas which were written by Georgia Tech personnel. Six copies of these revised specifications were forwarded to Mr. Charles McGrath of APL.

As stated above, this is the final Monthly Technical Status Report required under the referenced contract. The initial contract statement of work specified a Final Technical Report to be delivered to APL by 26 September 1975. This requirement was subsequently waived in favor of writing the above referenced antenna specifications. At this time, an official contract modification to delete the Final Report has not been received by Georgia Tech; however, it is understood that such a document is in preparation. The Sensor Systems Division appreciated this opportunity to work with the Applied Physics Laboratory and looks forward to future programs of mutual interest.

Respectfully submitted,

James W. Cofer
SATRACK Project Director

JWC:mh
Approved:

E. K. Reedy
Head, Systems Technology Branch

cc: R. B. Hester
R. M. Goodman, Jr.

APL SUBCONTRACT MONTHLY FISCAL REPORT

File: A-1617-100 CLC-15

For Period Ending 6/30/74

A-1617-100

Georgia Tech Research Institute

Contractor Georgia Institute of Technology   Contract No. Prime N00017-72-C-4401   Contract Amount $24,957

Type of Obligation	Expenditures (1) Current Month	(2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	2,971.00	11,432.60		700.00	12,665.00
Burden @ ___%					
Total	2,971.00	11,432.60		700.00	12,665.00
2. Manufacturing					
Labor					
Burden @ ___%					
Total					
3. Materials & Services	75.55	179.32			200.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	538.20	1,938.77		425.00	2,364.00
7. Other Direct Costs					
a Retirement Benefits	-	-		850.00	1,095.00
b. Computer	118.88	118.88		-	400.00
Total	118.88	118.88		850.00	1,495.00
8. Total (Lines 1 thru 7)	3,703.63	13,669.57		1,975.00	16,724.00
9. G&A @ 65 %	1,931.15	7,431.19		455.00	8,233.00
10. Total (Lines 8 and 9)	5,634.78	21,100.76		2,430.00	24,957.00
11. Fee or Profit					
12. Grand Total	5,634.78	21,100.76		2,430.00	24,957.00

Total Amount Invoiced as of 6/30/74 (Voucher No. 1 to 3 incl) $ 21,100.76   Submitted By ________ /12/74
Name   Date

Total Reimbursement Received to 6/30/74 (Voucher No. 1 to ____) $ 2,289.52   Supervisor, Accounting and Budgets

CLC-15

APL SUBCONTRACT MONTHLY FISCAL REPORT

For Period Ending 7/31/74

A-1617-100

Contractor Georgia Tech Research Institute Georgia Institute of Technology Contract No. Prime N00017-72-C-4401 Contract Amount $24,957

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	1,100.51	12,533.11		131.89	12,665.00
Burden @ ___%					
Total	1,100.51	12,533.11		131.89	12,665.00
2. Manufacturing					
Labor					
Burden @ ___%					
Total					
3. Materials & Services	31.37	210.69		214.31	425.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	437.32	2,376.09		-	2,376.09
7. Other Direct Costs					
a. Retirement	801.24	801.24		56.21	857.45
b. Computer	236.51	355.39		45.07	400.46
Total	1,037.75	1,156.63		101.28	1,257.91
8. Total (Lines 1 thru 7)	2,606.95	16,276.52		447.48	16,724.00
9. G&A @ 65 %	715.33	8,146.52		86.48	8,233.00
10. Total (Lines 8 and 9)	3,322.28	24,423.04		533.96	24,957.00
11. Fee or Profit					
12. Grand Total	3,322.28	24,423.04		533.96	24,957.00

Total Amount Invoiced as of 7/31/74 (Voucher No. 1 to 4 incl) $ 24,423.04

Total Reimbursement Received to 7/31/74 (Voucher No. 1 to 2) $ 15,465.98

Submitted By ______________ 8/12/74
Name Date

Supervisor, Accounting and Budgets

File: A-1617-020

ACC-15

APL SUBCONTRACT MONTHLY FISCAL REPORT

For Period Ending 12/31/74

A-1617-100

Contractor Georgia Tech Research Institute
Georgia Institute of Technology

Contract No. 600128 (Subcontract Prime N00017-72-C-4401)

Contract Amount 49,957.00

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	971.83	20,346.52		1,200.00	24,903.00
Burden @ ____%					
Total	971.83	20,346.52		1,200.00	24,903.00
2. Manufacturing					
Labor					
Burden @ ____%					
Total					
3. Materials & Services	422.50	1,320.05	53.76	100.00	1,610.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	170.00	3,887.57			3,967.00
7. Other Direct Costs					
a. Retirement	89.61	1,313.74		105.24	2,040.00
b. Computer	231.87	1,160.52		89.48	1,250.00
Total	321.48	2,474.26		194.72	3,290.00
8. Total (Lines 1 thru 7)	1,885.81	28,028.40	53.76	1,494.72	33,770.00
9. G&A @ 65 %	631.69	13,225.24		780.00	16,187.00
10. Total (Lines 8 and 9)	2,517.50	41,253.64	53.76	2,274.72	49,957.00
11. Fee or Profit					
12. Grand Total	2,517.50	41,253.64	53.76	2,274.72	49,957.00

Total Amount Invoiced as of 12/31/74 (Voucher No. 1 to 7 incl) $ 41,253.64

Total Reimbursement Received to 12/31/74 (Voucher No. 1 to 6) $ 38,736.14

Submitted By ________ Name 1/8/75 Date

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

APL SUBCONTRACT MONTHLY FISCAL REPORT

For Period Ending 1/31/75

A-1617-100

Contractor Georgia Tech Research Institute Georgia Institute of Technology Contract No. 600128 (Subcontract Prime N00017-72-C-4401) Contract Amount $ 49,957.00

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	1,360.86	21,707.38		1,000.00	24,903.00
Burden @ ____%					
Total	1,360.86	21,707.38		1,000.00	24,903.00
2. Manufacturing					
Labor					
Burden @ ____%					
Total					
3. Materials & Services	82.18	1,402.23		100.00	1,610.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	-	3,887.57		200.00	3,967.00
7. Other Direct Costs					
a. Retirement	55.61	1,369.35		87.70	2,040.00
b. Computer	53.74	1,214.26		100.00	1,250.00
Total	109.35	2,583.61		187.70	3,290.00
8. Total (Lines 1 thru 7)	1,552.39	29,580.79		1,487.70	33,770.00
9. G&A @ 65 %	884.56	14,109.80		650.00	16,187.00
10. Total (Lines 8 and 9)	2,436.95	43,690.59		2,137.70	49,957.00
11. Fee or Profit					
12. Grand Total	2,436.95	43,690.59		2,137.70	49,957.00

Total Amount Invoiced as of 1/31/75 (Voucher No. 1 to 8 incl) $ 43,690.59

Submitted By [illegible] 2/11/75
Name Date

Total Reimbursement Received to 1/31/75 (Voucher No. 1 to 6) $ 38,736.14

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

A-1617-100

A-1617-100

ACC-15

APL SUBCONTRACT MONTHLY FISCAL REPORT

Georgia Tech Research Institute
Georgia Institute of Technology

For Period Ending 2/28/75

Contractor ______ Contract No. 600128 (Subcontract Prime N00017-72-C-4401) Contract Amount $ 49,957.00

Type of Obligation	Expenditures (1) Current Month	(2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	$ 1,394.71	$ 23,102.09		$ 500.00	$ 24,828.00
Burden @ ____%					
Total	1,394.71	23,102.09		500.00	24,828.00
2. Manufacturing					
Labor					
Burden @ ____%					
Total					
3. Materials & Services	10.51	1,412.74			1,610.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	159.34	4,046.91			4,046.91
7. Other Direct Costs					
a. Retirement	68.95	1,438.30		43.85	2,033.42
b. Computer	56.62	1,270.88		-	1,300.42
Total	125.57	2,709.18		43.85	3,333.84
8. Total (Lines 1 thru 7)	1,690.13	31,270.92		543.85	33,818.75
9. G&A @ 65 %	906.56	15,016.36		325.00	16,138.25
10. Total (Lines 8 and 9)	2,596.69	46,287.28		868.85	49,957.00
11. Fee or Profit					
12. Grand Total	2,596.69	46,287.28		868.85	49,957.00

Total Amount Invoiced as of 2/28/75 (Voucher No. 1 to 9 incl) $ 46,287.28

Total Reimbursement Received to 2/28/75 (Voucher No. 1 to 7) $ 41,253.64

Submitted By ______ 3/12/75
Name Date

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

A-1617-100

ACC-15

APL SUBCONTRACT MONTHLY FISCAL REPORT

For Period Ending 3/31/75

Contractor Georgia Tech Research Institute Georgia Institute of Technology Contract No. 600128 (Subcontract Prime N00017-72-C-4401) Contract Amount $ 49,957.00

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	$ 76.02	$ 23,178.11		300.00	$ 24,828.00
Burden @ ____%					
Total	76.02	23,178.11		300.00	24,828.00
2. Manufacturing					
Labor					
Burden @ ____%					
Total					
3. Materials & Services	3.66	1,416.40			1,610.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	-	4,046.91			4,046.91
7. Other Direct Costs					
a. Retirement	62.36	1,500.66		26.31	2,033.42
b. Computer	3.08	1,273.96			1,300.42
Total	65.44	2,774.62		26.31	3,333.84
8. Total (Lines 1 thru 7)	145.12	31,416.04		326.31	33,818.75
9. G&A @ 65 %	49.41	15,065.77		195.00	16,138.25
10. Total (Lines 8 and 9)	194.53	46,481.81		521.31	49,957.00
11. Fee or Profit					
12. Grand Total	194.53	46,481.81		521.31	49,957.00

Total Amount Invoiced as of 3/31/75 (Voucher No. 1 to 10 incl) $ 46,481.81

Total Reimbursement Received to 3/31/75 (Voucher No. 1 to 8) $ 43,690.59

Submitted By ________ 4/10/75
Name Date

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

A-1617-100

ACC-15

APL SUBCONTRACT MONTHLY FISCAL REPORT

Contractor Georgia Tech Research Institute Georgia Institute of Technology

For Period Ending 4/30/75

Contract No. 600128 (Subcontract Prime N00017-72-C-4401)

Contract Amount $ 49,957.00

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	544.67	23,722.78		500.00	24,828.00
Burden @ ____%					
Total	544.67	23,722.78		500.00	24,828.00
2. Manufacturing					
Labor					
Burden @ ____%					
Total					
3. Materials & Services	3.24	1,419.64		-	1,610.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	-	4,046.91		-	4,046.91
7. Other Direct Costs					
a. Retirement	5.15	1,505.81		43.85	2,033.42
b. Computer	-	1,273.96		-	1,300.42
Total	5.15	2,779.77		43.85	3,333.84
8. Total (Lines 1 thru 7)	553.06	31,969.10		543.85	33,818.75
9. G&A @ 65 %	354.04	15,419.81		325.00	16,138.25
10. Total (Lines 8 and 9)	907.10	47,388.91		868.85	49,957.00
11. Fee or Profit					
12. Grand Total	907.10	47,388.91		868.85	49,957.00

Total Amount Invoiced as of 4/30/75 (Voucher No. 1 to 11 incl) $ 47,388.91

Total Reimbursement Received to 4/30/75 (Voucher No. 1 to 9) $ 46,287.28

Submitted By [signature] 5/15/75
Name Date

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

A-1617-100 ACC-15

APL SUBCONTRACT MONTHLY FISCAL REPORT

For Period Ending 5/31/75

Contractor Georgia Tech Research Institute Georgia Institute of Technology

Contract No. 600128 (Subcontract Prime N00017-72-C-4401)

Contract Amount $ 49,957.00

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	439.03	24,161.81		200.00	24,828.00
Burden @ ____ %					
Total	439.03	24,161.81		200.00	24,828.00
2. Manufacturing					
Labor					
Burden @ ____ %					
Total					
3. Materials & Services	8.82	1,428.46		-	1,610.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	-	4,046.91		-	4,046.91
7. Other Direct Costs					
a. Retirement	22.95	1,528.76		17.54	2,033.42
b. Computer	-	1,273.96		-	1,300.42
Total	22.95	2,802.72		17.54	3,333.84
8. Total (Lines 1 thru 7)	470.80	32,439.90		217.54	33,818.75
9. G&A @ 65 %	285.37	15,705.18		130.00	16,138.25
10. Total (Lines 8 and 9)	756.17	48,145.08		347.54	49,957.00
11. Fee or Profit					
12. Grand Total	756.17	48,145.08		347.54	49,957.00

Total Amount Invoiced as of 5/31/75 (Voucher No. 1 to 12 incl) $ 48,145.08

Total Reimbursement Received to 5/31/75 (Voucher No. 1 to 10) $ 46,481.81

Submitted By ______________ Name 6/13/75 Date

Supervisor, Accounting & Budgets Title

Orig. & 1 copy: APL Contract Representative

APL SUBCONTRACT MONTHLY FISCAL REPORT

A-1617-100

ACC-15

For Period Ending 6/30/75

Contractor Georgia Tech Research Institute Georgia Institute of Technology

Contract No. 600128 (Subcontract Prime N00017-72-C-4401)

Contract Amount $ 49,957.00

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	98.97	24,260.78		200.00	24,828.00
Burden @ ____%					
Total	98.97	24,260.78		200.00	24,828.00
2. Manufacturing					
Labor					
Burden @ ____%					
Total					
3. Materials & Services	4.20	1,432.66			1,610.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	-	4,046.91			4,046.91
7. Other Direct Costs					
a. Retirement	33.18	1,561.94		17.54	2,033.42
b. Computer	-	1,273.96		-	1,300.42
Total	33.18	2,835.90		17.54	3,333.84
8. Total (Lines 1 thru 7)	136.35	32,576.25		217.54	33,818.75
9. G&A @ 65 %	64.33	15,769.51		130.00	16,138.25
10. Total (Lines 8 and 9)	200.68	48,345.76		347.54	49,957.00
11. Fee or Profit					
12. Grand Total	200.68	48,345.76		347.54	49,957.00

Total Amount Invoiced as of 6/30/75 (Voucher No. 1 to 13 incl) $ 48,345.76

Total Reimbursement Received to 6/30/75 (Voucher No. 1 to 11) $ 47,388.91

Submitted By ____________ 7/11/75
Name Date

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

APL SUBCONTRACT MONTHLY FISCAL REPORT A-1617-100 ACC-15

For Period Ending 7/31/75

Contractor Georgia Tech Research Institute Georgia Institute of Technology

Contract No. 600128 (Subcontract Prime N00017-72-C-4401)

Contract Amount 49,957.00

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	199.58	24,460.36		500.00	25,051.04
Burden @ ____%					
Total	199.58	24,460.36		500.00	25,051.04
2. Manufacturing					
Labor					
Burden @ ____%					
Total					
3. Materials & Services	8.28	1,440.94			1,610.00
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	-	4,046.91			4,046.91
7. Other Direct Costs					
a. Retirement	8.68	1,570.62			1,570.62
b. Computer	-	1,273.96			1,300.42
c. Fringe Benefits	29.94	29.94		75.00	118.54
Total	38.62	2,874.52		75.00	2,989.58
8. Total (Lines 1 thru 7)	246.48	32,822.73		575.00	33,697.53
9. G&A @ 62 %	123.74	15,893.25		310.00	16,259.47
10. Total (Lines 8 and 9)	370.22	48,715.98		885.00	49,957.00
11. Fee or Profit					
12. Grand Total	370.22	48,715.98		885.00	49,957.00

Total Amount Invoiced as of 7/31/75 (Voucher No. 1 to 14 incl) $ 48,715.98

Total Reimbursement Received to 7/31/75 (Voucher No. 1 to 12) $ 48,145.08

Submitted By ____________ Name 8/18/75 Date

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

A-1617-100

ACC-15

APL SUBCONTRACT MONTHLY FISCAL REPORT

For Period Ending 8/31/75

Contractor Georgia Tech Research Institute Georgia Institute of Technology Contract No. 600128 (Subcontract Prime N00017-72-C-4401) Contract Amount $ 49,957.00

Type of Obligation	Expenditures (1) Current Month	Expenditures (2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments) (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	$ 471.48	$ 24,931.84		$ 249.87	$ 25,181.71
Burden @ ___%					
Total	471.48	24,931.84		249.87	25,181.71
2. Manufacturing					
Labor					
Burden @ ___%					
Total					
3. Materials & Services	7.08	1,448.02		-	1,448.02
4. Equipment & Tooling					
5. Subcontracts					
6. Travel		4,046.91			4,046.91
7. Other Direct Costs					
a. Retirement	17.70	1,588.32		22.34	1,610.66
b. Computer	-	1,273.96		-	1,273.96
c. Fringe Benefits	(29.94)	-			-
Total	(12.24)	2,862.28		22.34	2,884.62
8. Total (Lines 1 thru 7)	466.32	33,289.05		272.21	33,561.26
9. G&A @ 68 %	332.58	16,225.83		169.91	16,395.74
10. Total (Lines 8 and 9)	798.90	49,514.88		442.12	49,957.00
11. Fee or Profit					
12. Grand Total	798.90	49,514.88		442.12	49,957.00

Total Amount Invoiced as of 8/31/75 (Voucher No. 1 to 15 incl) $ 49,514.88

Total Reimbursement Received to 8/31/75 (Voucher No. 1 to 13) $ 48,345.76

Submitted By ________ Name ________ Date

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

ORIGINAL

APL SUBCONTRACT MONTHLY FISCAL REPORT

A-1617-100 ACC-15

For Period Ending 9/30/75

Contractor Georgia Tech Research Institute Georgia Institute of Technology

Contract No. 600128 (Subcontract Prime N00017-72-C-4401)

Contract Amount 49,957.00

Type of Obligation	Expenditures (1) Current Month	(2) Cumulative Total	(3) Outstanding Commitments	(4) Estimated Costs (Expenditures plus Commitments (5) Next Month	(6) Total at Compl.
1. Engineering					
Labor	230.94	25,162.78			25,162.78
Burden @ ___%					
Total	230.94	25,162.78			25,162.78
2. Manufacturing					
Labor					
Burden @ ___%					
Total					
3. Materials & Services	4.44	1,452.46			1,452.46
4. Equipment & Tooling					
5. Subcontracts					
6. Travel	-	4,046.91			4,046.91
7. Other Direct Costs					
a. Retirement	39.81	1,628.13		9.89	1,638.02
b. Computer	-	1,273.96			1,273.96
Total	39.81	2,902.09		9.89	2,911.98
8. Total (Lines 1 thru 7)	275.19	33,564.24			33,574.13
9. G&A @ 68 %	157.04	16,382.87			16,382.87
10. Total (Lines 8 and 9)	432.23	49,947.11			49,957.00
11. Fee or Profit					
12. Grand Total	432.23	49,947.11			49,957.00

Total Amount Invoiced as of 9/30/75 (Voucher No. 1 to 16 incl) $ 49,947.11

Total Reimbursement Received to 9/30/75 (Voucher No. 1 to 14) $ 48,715.98

Submitted By, ____________ 10/31/75
Name Date

Supervisor, Accounting & Budgets
Title

Orig. & 1 copy: APL Contract Representative

File: A-1617-100

FINAL TECHNICAL REPORT

SATRACK MISSILE ANTENNA STUDY

EES/GIT Project A–1617–100

By

J. W. Cofer, Jr. and D. G. Bodnar

Prepared for

APPLIED PHYSICS LABORATORY
THE JOHNS HOPKINS UNIVERSITY
Silver Spring, Maryland 20910

Under

APL/JHU Subcontract 600128, TASK 2

August 1974

1974

ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia 30332

ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia 30332

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Under

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and
APL/JHU Subcontract 600128, Task 2

August 1974

ABSTRACT

Under Subcontract 600128, Task 2 with The Applied Physics Laboratory of The Johns Hopkins University, the Engineering Experiment Station at the Georgia Institute of Technology has performed an antenna design study in support of the Navy's SATRACK program. Investigations, both theoretical and experimental, were directed toward achieving omni-directional coverage from the SATRACK vehicle at the frequencies 150 MHz, 400 MHz, and 1600 MHz. Typical calculated coverage levels for several different arrays are included along with a survey of applicable element types.

Several breadboard microstrip patch radiators were fabricated and tested in an effort to develop a lightweight,dual-frequency element.

A time-diversity system proposed by APL and LMSC was analyzed, and the results are included herein.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperative spirit and technical efforts of numerous persons at the Applied Physics Laboratory, Lockheed Missile and Space Company, and the Georgia Institute of Technology. In particular, the technical direction received from Messrs. R. B. Hester and E. E. Westerfield and Dr. C. C. Kilgus of APL and Mr. R. M. Goodman, Jr., of Georgia Tech are appreciated. The mock-up information and corresponding measured data supplied by Messrs. D. A. Yamada, S. R. Altizer, and J. B. Wade of LMSC were invaluable. The technical consultations, laboratory measurements, and computer programming provided by Messrs. J. M. Schuchardt, J. N. Newton, and C. E. Summers, respectively, of Georgia Tech were of key importance in the successful completion of this work.

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I. INTRODUCTION

The Sensor Systems Division of the Georgia Tech Engineering Experiment Station has for the past six months been under contract (APL/JHU) Subcontract 600128, Task 2 to the Applied Physics Laboratory (APL)of the Johns Hopkins University to perform an antenna study in support of the Navy's SATRACK program. The major results and findings of this study are documented in this report.

This work has basically taken the format of the following five tasks. (1) Conduct independent antenna design studies; (2) Model on the computer the electromagnetic environment of the antenna located on the vehicle; (3) Analyze both the data and the antenna designs of the Lockheed Missile and Space Company (LMSC) of Sunnyvale, California; (4) Breadboard elements; (5) Provide antenna representation for APL at program contractor meetings.

Initially APL was concerned only with the two frequencies 150 MHz and 400 MHz for application to this program. Later in the contract APL's interest changed to 400 MHz and 1600 MHz. Consequently, this report is basically divided into three areas of study, 150 MHz, 400 MHz, and 1600 MHz. An additional section is also provided to document the chronology of project events. Also, a conclusion section which summarized the work completed and presents Georgia Tech's recommendations for future work that needs to be done is provided.

A radiation specification,which was generated during the course of this study,for the 150 and 400 MHz systems is also included as Appendix A.

II. CHRONOLOGY OF PROJECT EVENTS

This section documents the major events such as meetings and report submission which transpired on APL/JHU Subcontract 600128, Task 2. It is intended to serve as a history of significant communications and not necessarily an outline of the work performed under this contract. Such a work outline is contained in the Table of Contents.

In January 1974, Georgia Tech and APL personnel discussed the SATRACK program and some of its related antenna problems. APL desired antenna systems operating at 150 MHz and 400 MHz whose radiation patterns approached omni-directional over the entire sphere surrounding the SATRACK vehicle. Georgia Tech personnel suggested that they possibly could make a contribution to this program by performing detailed antenna design studies, a limited amount of hardware breadboarding, fabrication, and testing, and providing liaison between APL, the Navy, Lockheed, and the various other program contractors.

On February 14 and 15, 1974 Mr. J. M. Schuchardt of Georgia Tech visited the facilities of the Applied Physics Laboratory to attend a meeting of contractors on the SATRACK program. In attendance at this meeting were Navy, APL and Lockheed personnel. Lockheed presented data at this meeting which indicated that both the 400 and 150 MHz systems needed work in the area of antenna design. The coverage level presented for both of these frequencies indicated that the performance was somewhat less than satisfactory. At this time Mr. Schuchardt was invited to visit the Lockheed facilities at Sunnyvale, California at the earliest possible time.

On February 27, Mr. J. W. Cofer and J. M. Schuchardt of Georgia Tech visited Lockheed Missile and Space Company in Sunnyvale to observe the vehicle mock up, the type of antennas placed on the mock up, and the testing facilities. At this time Messrs. Cofer and Schuchardt met with Messrs. S. R. Altizer, W. J. Parks, and J. B. Wade of LMSC. During this meeting, limited discussion was given to the design of the 150 MHz element. Mr. G. R. Hoople of LMSC, the designer of both elements, was unfortunately unavailable for the meeting. During this visit, Tech personnel observed the measurement procedures and equipment used for obtaining the radiation distribution plots over the entire sphere.

On June 28, 1974, Mr. J. W. Cofer of Georgia Tech visited APL to attend a SATRACK contractors meeting and to participate in the writing of antenna specifications for the 150 and 400 MHz frequencies. During this meeting with Mr. E. E. Westerfield and Dr. C. C. Kilgus of APL, a specification format was drawn up, but a concensus opinion as to the required coverage level could not be formulated at this time. The following week Messrs. Hester, Kilgus, Westerfield, Goodman, and Cofer talked on the phone concerning the system requirements for SATRACK program and arrived at numbers that should be placed in this specification. This resulting specification may be summarized as follows: The coverage for the 150 MHz system will be at least -13 dB with respect to a circularly polarized isotropic source over 90% of the total sphere and the 400 MHz system will have a coverage level of at least -10 dB with respect to a circularly polarized isotropic source over 90% of the sphere.

On 25 April 1974, Mr. J. M. Schuchardt of Georgia Tech attended a SATRACK range safety meeting at the Interstate Electronics Corporation (IEC) in Anaheim, California. This meeting was also attended by APL, IEC, and Navy personnel. It was learned at this meeting that consideration was being given to the Air Force's Global Positioning System (GPS) with the missile antennas operating at the frequencies of 400 and 1600 MHz. He also learned that APL was considering signal processing techniques for combining the antenna patterns so as to form no nulls (i.e.,video addition of the signals). During this meeting Mr. Schuchardt discussed the implication of the new specification with Mr. Jack Wade of LMSC. Also, Mr. Wade described a new 150-MHz antenna approach consisting of a two-element array which supposedly performs significantly better than the array presented in February. During this meeting, Mr. Schuchardt requested that Georgia Tech be supplied with copies of paper tapes and radiation distribution plots for all candidate antennas investigated by LMSC.

On 6 May 1974, Dr. C. C. Kilgus of APL called Georgia Tech and requested that Georgia Tech project personnel accompany him in a visit to the LMSC facilities on Tuesday, 14 May 1974, to discuss the antennas of the SATRACK program. On 7 May 1974, Mr. J. W. Cofer of Georgia Tech wrote a letter to Mr. Sid Altizer of LMSC notifying him of this impending meeting and requesting that the following data items be available at this meeting: radiation contour plots, paper tape of contour plots, absolute gain levels of the contour plots referenced to a circularly-polarized isotropic source, antenna efficiency, and complete distribution of radiated power.

On 14 May 1974, Dr. C. C. Kilgus of APL and Dr. D. G. Bodnar of Georgia Tech visited Lockheed in Sunnyvale to discuss the performance of the 150-MHz and 400-MHz SATRACK antennas. This meeting was also attended by Messrs. J. B. Wade, K. K. Wagy, and G. R. Hoople of Lockheed, Mr. R. L. Hickerson of APL, and Mr. R. H. Duhamel, a consultant to Lockheed. During this meeting, Lockheed presented a new 150-MHz antenna design which consisted of a four-element array with each element being a blade-type antenna over a ground plane. The performance of this antenna was also discussed during this meeting. Over 90% of the sphere the gain was greater than -14.1 dBi. Although this figure was approximately 1 dB out of the specification, it was considered by both Dr. Kilgus and Georgia Tech personnel to be acceptable. Georgia Tech requested the paper tape for this data so that an independent analysis might be carried out. Also during this meeting, Dr. Duhamel presented his theoretical results for loop antennas located on a truncated cylinder. The results of his analysis indicated that about 10 elements would be required at 400 MHz to obtain the same type of coverage as was obtained at 150 MHz. It was not known at this time if Lockheed planned to use this many elements although they had indicated a preference for a somewhat smaller number. It was decided after this meeting by Drs. Kilgus and Bodnar that the course Georgia Tech should follow during the remainder of the study should be as follows. (1) Analyze the Lockheed 150-MHz data and compare our results with those of Lockheed; (2) Evaluate the number of antennas which we feel are needed at 400 MHz and let APL know of these results; (3) Investigate alternate elements especially at 400 MHz.

On 22 May 1974, Mr. R. B. Hester of APL called Mr. R. M. Goodman, Jr. Georgia Tech to ask for a quick analysis of the wraparound antenna operating at 1.6 GHz. It seems that the possibility of going to this higher frequency is a very real one due to the potential for using GPS. Messrs. J. M. Schuchardt and J. W. Cofer responded to this request by TWX and by letter on 23 May 1974 by investigating the design principles of the wraparound antenna and the geometry of the SATRACK vehicle and making the following comments:

(1) The antenna size would be at most 1/4" thick and 12" high (axial length) and would wrap completely around the vehicle.

(2) The corporate feed structure impedances would probably be between 25 and 100 ohms and therefore, of no real problem.

(3) The corporate feed structure has only one input but could branch out to as many as 32 or 64 different feed points.

(4) The 32 feeds require nominally 30 half wavelength transformers. We estimate 2.5 dB line loss for these transformers.

(5) Using Munson's criteria, a 99% coverage level of -11 dBi for linear (-14 dBi for circular) was calculated.

On 28 May 1974, Mr. J. W. Cofer of Georgia Tech called Mr. G. R. Hoople of Lockheed to discuss the format of the data on the tape which Lockheed forwarded to Tech. It seems that the tape contained too much data--that is, too many rows and too many columns--and contained certain glitches in the data. Mr. Hoople said that they encountered the same problems, but that they read the first 180 Φ values in the first 90 θ rows and threw away the rest of the data. They also edited out any spikes which appeared in the data as this was a problem in the recording equipment.

On 4 June 1974, a Special Technical Report which documented the results of this tape analysis was published by Messrs. J. W. Cofer and C. E. Summers of Georgia Tech. This report was submitted to the Applied Physics Lab on 5 June 1974 during a facility visit by J. W. Cofer and D. G. Bodnar. The results of the Tech analysis were very close to those obtained by the Lockheed Missile and Space Company.

On 19 June 1974 Mr. R. B. Hester of APL called to request that Mr. J. W. Cofer of Georgia Tech accompany APL in a contractors meeting to be held at the LMSC facilities in Anaheim, California. This meeting was to be the first time that the GPS system was to be formally introduced to Lockheed.

On July 2, 1974 Mr. J. W. Cofer accompanied Mr. R. B. Hester and a contingent of APL personnel to discuss the implications of this new GPS frequency at LMSC. During this meeting and the second meeting on July 3, it became apparent that a discrepancy existed in the system planned. Lockheed proposed to use either 2 or 4 elements located on the vehicle so as to achieve the desired radiation characteristics (i.e. approximately -12 dBi over 90% of the sphere), even though this combination would produce many nulls and consequently phase discontinuities in the pattern. Mr. Westerfield of APL was quite concerned that this would cause the tracking loops to drop lock. This problem was not solved at this meeting. A Technical Memorandum was presented by J. W. Cofer to APL and LMSC suggesting the use of a biconical horn; however, it was found that needed element location was not available.

On 25 July 1974, Dr. C. C. Kilgus of APL called Dr. D. G. Bodnar of Georgia Tech to say that Lockheed has proposed a two channel time diversified receiver to be used on the SATRACK vehicle. Using this concept two elements would be placed 180° apart and combined in phase. Another two elements would be displaced by 90° from these two and also combined in phase. The input to the translator would be switched between the pairs and the receiver on the ground would then select the strongest of this pair. Dr. Kilgus stated that APL was interested in the type of phase variation which might be obtained from these two element arrays. Georgia Tech agreed to investigate this phase characteristic and report these back to APL as soon as possible.

On 30 July 1974 Dr. D. G. Bodnar and J. W. Cofer called Dr. Kilgus to relay the results of this phased investigation. They reported at this time that due to the radial displacement of the elements from the center of the vehicle that a large sinusoidal phase variation which had a peak value of several hundred degrees would be present. However, very few if any, instantaneous phase jumps were present; therefore, this approach of time diversity appears feasible. At this time, Dr. Kilgus requested that Georgia Tech investigate elements suitable for use at 1600 MHz and that Dr. Bodnar and Mr. Cofer accompany him on a facility visit to LMSC on 14 August 1974 to discuss these elements.

III. 150-MHz STUDIES

When Georgia Tech initially joined the SATRACK team, the antenna performance at both 150 and 400 was somewhat less than satisfactory. Tech personnel began investigating methods for improving this performance from the standpoints of array design and element selection. Two theoretical schemes (termed scalar and moment methods) were employed to analyze the array requirements. Several microstrip antennas were fabricated and tested in an effort to find a lightweight high-efficiency element which also had the potential to be dual frequency. These topics in addition to analyses of LMSC's two-element and four-element 150-MHz arrays are included in this section.

A. Scalar Calculations

A digital computer program was written which calculated the total far-field radiation pattern from a circular array of elements as shown in Figure 1. This calculation, termed scalar since it neglects polarization, is useful for observing the effect of varying the number of elements. The total calculated field due to N elements using this method is found from the equation

$$E_t(\theta_i, \Phi_j) = \sum_{n=1}^{N} E_n(\theta_i, \Phi_j) \exp(-j\Psi_n) \exp(-j\beta R_n) \qquad (1)$$

where E_t is the total far-field voltage pattern,

E_n is the individual element voltage pattern,

Ψ_n is the individual element phase,

$\beta = 2\pi/\lambda$,

R_n is the distance from the n^{th} element to the far-field point, and

θ_i, Φ_j are the standard spherical angular coordinates as shown in Figure 1.

A number of other useful computer subroutines have been written to complement this program. For example, subroutines were generated for calculating the directivity and statistical power distribution and plotting

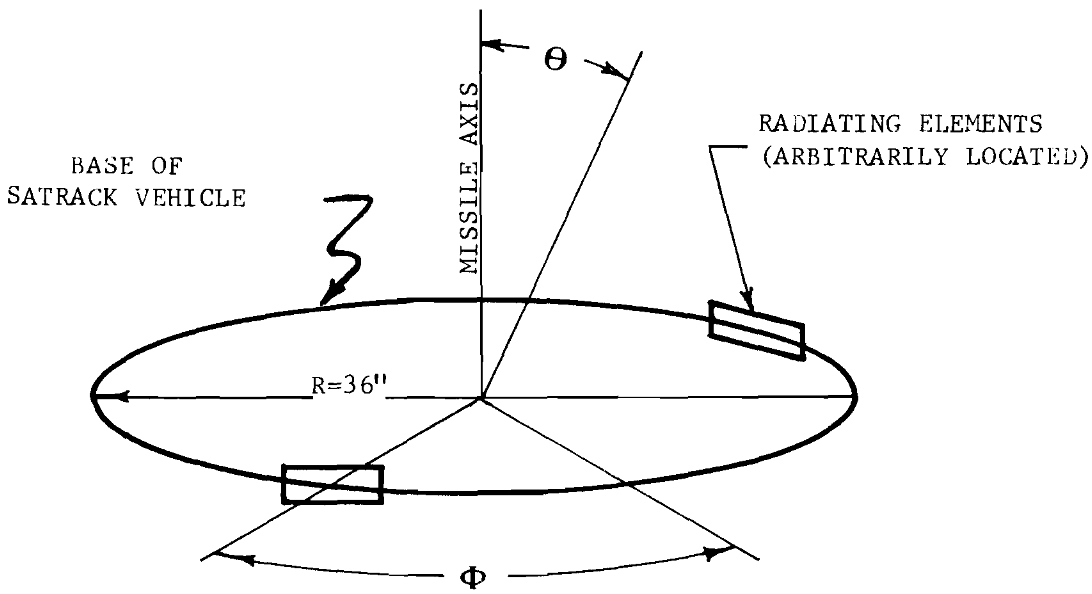


Figure 1. SATRACK geometry used in scalar calculations.

the data in either three-dimensional, line contour, or standard rectangular radiation distribution formats. Patterns were calculated for a large number of element spacings and phasings, and their power coverage levels are included herein. For example, three-dimensional (as a function of θ and Φ) radiation patterns (power) for four equally-spaced elements having cardioid-shaped patterns are shown in Figures 2 and 3 for relative element phasings of (0^o, 0^o, 180^o, 180^o) and (0^o, 180^o, 0^o, 180^o), respectively. This same data for the latter of these arrays is shown in the format of rectangular and polar radiation distribution plots in Figures 4 and 5, respectively.

The calculated coverage levels for all 150-MHz array investigated are shown in Figure 6, and the level corresponding to certain selected percentages (e.g. 50%, 90%, 95%) are tabulated in Table I. The levels in Table I have been adjusted to include the directivity but do not include any system losses such as polarization (3 dB for circular), efficiency, cable, or power divider. These losses typically should average about 7-8 dB. As can be seen from Table I, most of the arrays are equivalent at the 50% coverage level; however, they differ somewhat at the 90% level, and differ significantly at the 95% level. The two-element array with a relative phasing of (0^o,0^o) and the two four-element arrays having phasings of 0^o,0^o,0^o,0^o) and (0^o,90^o, 180^o, 270^o) appear to be the most promising candidates.

It is recognized that the scalar approach has its limitations in that vehicle coupling, shadowing, and depolarization effects have been ignored; however, it is felt that such calculations do shed considerable light on the effect of increasing or decreasing the number of elements. In order to better account for the shadowing and coupling effects, a moment method analysis was also included, and the results are presented in the following paragraphs.

B. Moment Methods

In this section, the effect of the vehicle on the element pattern will be calculated and included using the moment method [1] of evaluating electromagnetic fields. Since the vehicle geometry is too complicated for mathematical calculations, a simple model was used in the evaluation. The SATRACK vehicle was approximated by a perfectly conducting cone/cylinder configuration as shown in Figure 7. A perfectly conducting disk covers the bottom of the cylinder. The dimension parameters shown in Figure 7 were chosen to approximate the last stage of the vehicle. The upper portion of the vehicle was

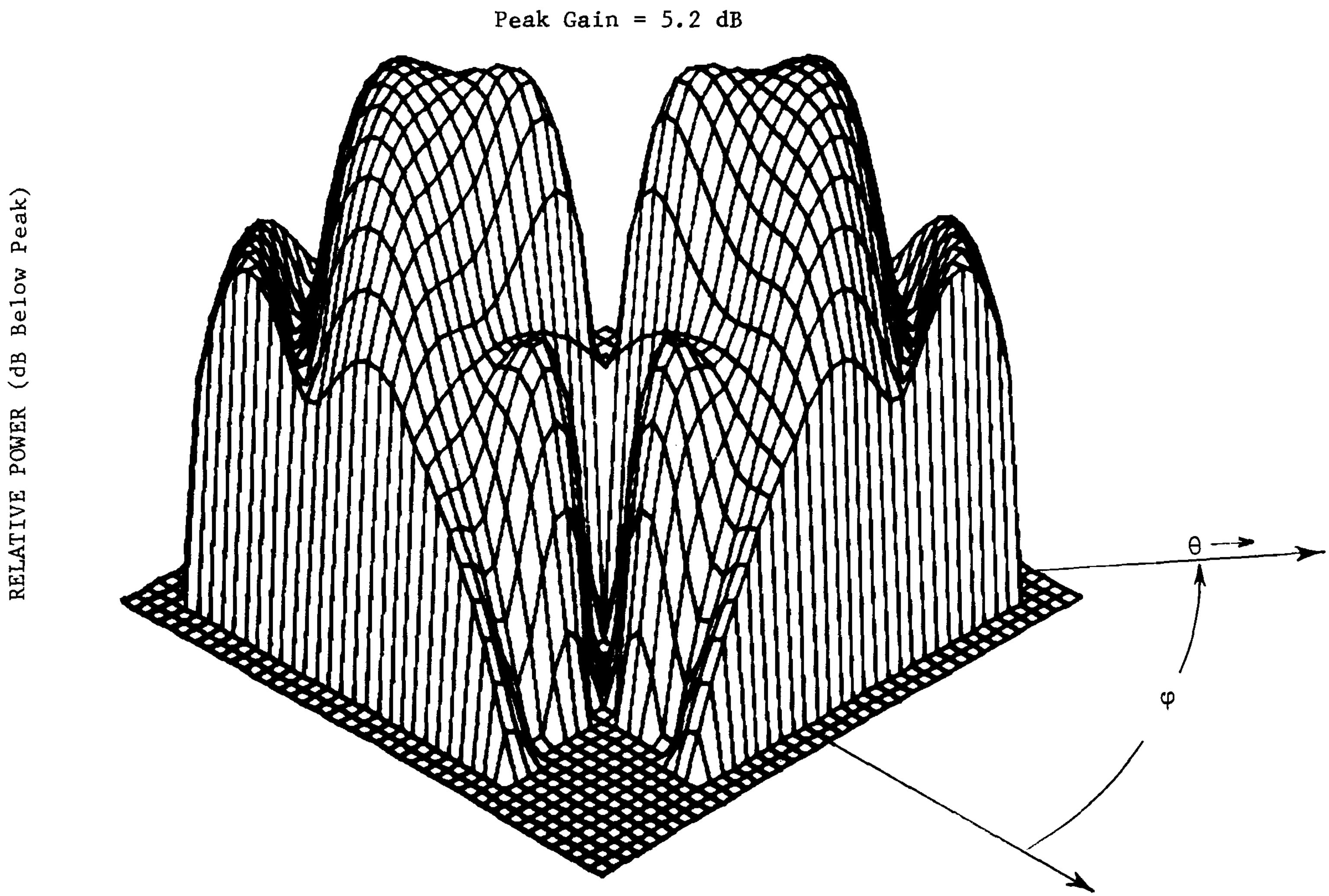


Figure 2. Three-dimensional calculated pattern for the phase sequence (0,0, 180, 180).

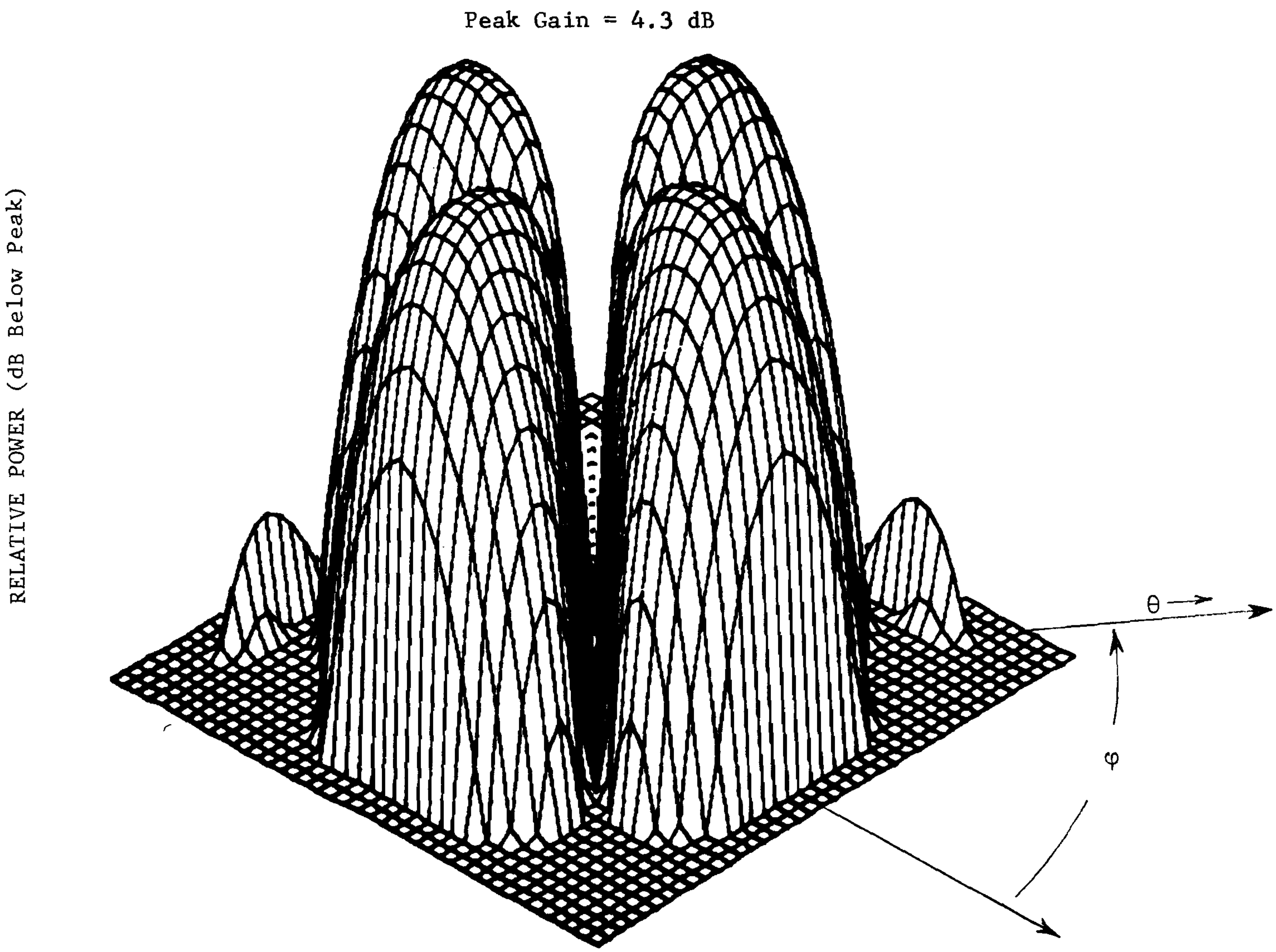


Figure 3. Three-dimensional calculated pattern for the phase sequence (0,180,0,180).

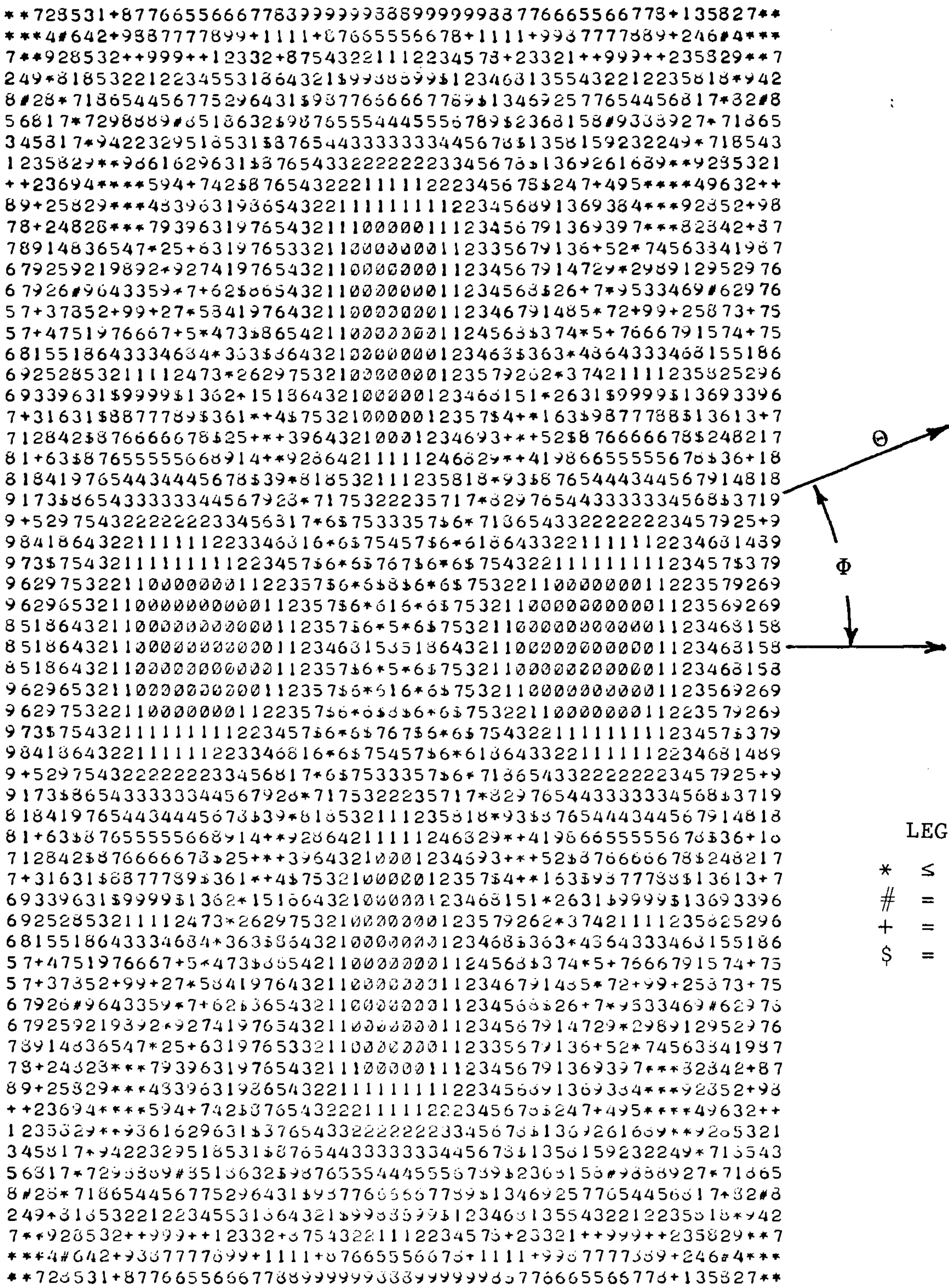
```
                Θ →
  0.00   8629764321110000000000000111234679268
  5.00   963$86432211000000000000011223468$369
 10.00   +74186543211100000000000111234568147+
 15.00   1852976443221111111111111223446792581
 20.00   3+63$87654332222222222222223345678$36+3
 25.00   52842$8765544444443444444455678$24825
 30.00   74+7421988776666666666666778891247+47
 35.00   183+864321$$$99999999999$$$123468+381
 40.00   749641+98766655555555555666789+146947
 45.00   *************************************
 50.00   749641+98766655555555555666789+146947
 55.00   183+864321$$$99999999999$$$123468+381
 60.00   74+7421988776666666666666778891247+47
 65.00   52842$8765544444443444444455678$24825
 70.00   3+63$87654332222222222222223345678$36+3
 75.00   1852976443221111111111111223446792581
 80.00   +74186543211100000000000111234568147+
 85.00   963$86432211000000000000011223468$369
 90.00   8629764321110000000000000111234679268
 95.00   963$86432211000000000000011223468$369
100.00   +74186543211100000000000111234568147+
105.00   1852976443221111111111111223446792581
110.00   3+63$87654332222222222222223345678$36+3
115.00   52842$8765544444443444444455678$24825
120.00   74+7421988776666666666666778891247+47
125.00   183+864321$$$99999999999$$$123468+381
130.00   749641+98766655555555555666789+146947
135.00   *************************************
140.00   749641+98766655555555555666789+146947
145.00   183+864321$$$99999999999$$$123468+381
150.00   74+7421988776666666666666778891247+47
155.00   52842$8765544444443444444455678$24825
160.00   3+63$87654332222222222222223345678$36+3
165.00   1852976443221111111111111223446792581
170.00   +74186543211100000000000111234568147+
175.00   963$86432211000000000000011223468$369
180.00   8629764321110000000000000111234679268
185.00   963$86432211000000000000011223468$369
190.00   +74186543211100000000000111234568147+
195.00   1852976443221111111111111223446792581
200.00   3+63$87654332222222222222223345678$36+3
205.00   52842$8765544444443444444455678$24825
210.00   74+7421988776666666666666778891247+47
215.00   183+864321$$$99999999999$$$123468+381
220.00   749641+98766655555555555666789+146947
225.00   *************************************
230.00   749641+98766655555555555666789+146947
235.00   183+864321$$$99999999999$$$123468+381
240.00   74+7421988776666666666666778891247+47
245.00   52842$8765544444443444444455678$24825
250.00   3+63$87654332222222222222223345678$36+3
255.00   1852976443221111111111111223446792581
260.00   +74186543211100000000000111234568147+
265.00   963$86432211000000000000011223468$369
270.00   8629764321110000000000000111234679268
275.00   963$86432211000000000000011223468$369
280.00   +74186543211100000000000111234568147+
285.00   1852976443221111111111111223446792581
290.00   3+63$87654332222222222222223345678$36+3
295.00   52842$8765544444443444444455678$24825
300.00   74+7421988776666666666666778891247+47
305.00   183+864321$$$99999999999$$$123468+381
310.00   749641+98766655555555555666789+146947
315.00   *************************************
320.00   749641+98766655555555555666789+146947
325.00   183+864321$$$99999999999$$$123468+381
330.00   74+7421988776666666666666778891247+47
335.00   52842$8765544444443444444455678$24825
340.00   3+63$87654332222222222222223345678$36+3
345.00   1852976443221111111111111223446792581
350.00   +74186543211100000000000111234568147+
355.00   963$86432211000000000000011223468$369
```

Φ (DEGREES) ↓

LEGEND

*	≤ - 40
#	= - 30
+	= - 20
$	= - 10

Figure 4. Rectangular radiation distribution plot for a four-element 150-MHz array having a relative element phase sequence of (0°, 180°, 0°, 180°).



LEGEND

*	≤	- 40
#	=	- 30
+	=	- 20
$	=	- 10

Figure 5. Polar radiation distribution plot for a four-element 150-MHz array having a relative element phase sequence of (0°, 180°, 0°, 180°).

TABLE I

SIGNIFICANT CALCULATED COVERAGE LEVELS FOR SEVERAL DIFFERENT ARRAYS OPERATING AT 150 MHz ON THE SATRACK VEHICLE. ALL ELEMENTS HAVE A CARDIOID-SHAPED* PATTERN.

Antenna Description			Coverage level** (dB w.r.t. Isotropic, Linear)		
Number of Elements	Phase Sequence (°)	Directivity	50% Level	90% Level	95% Level
1	0	3.5	0.1	-13.5	-19.5
2	0,0	3.7	-0.3	- 4.8	- 6.0
2	0,180	2.9	0.4	- 7.6	-12.6
4	0,0,0,0	4.6	-0.6	- 6.6	- 7.8
4	0,180,0,180	4.3	-1.6	-14.0	***
4	0,0,180,180	5.2	-2.3	-13.8	***
4	0,90,180,270	3.6	-0.6	- 6.7	- 8.2

* $E(\theta,\Phi) = \sqrt{(1 + \sin\theta)(1 + \cos\Phi)}$

** Coverage levels refer to the percent of the total sphere having power levels greater than or equal to the level indicated. These figures do not include polarization, efficiency, and component losses.

*** Outside range of calculated numbers

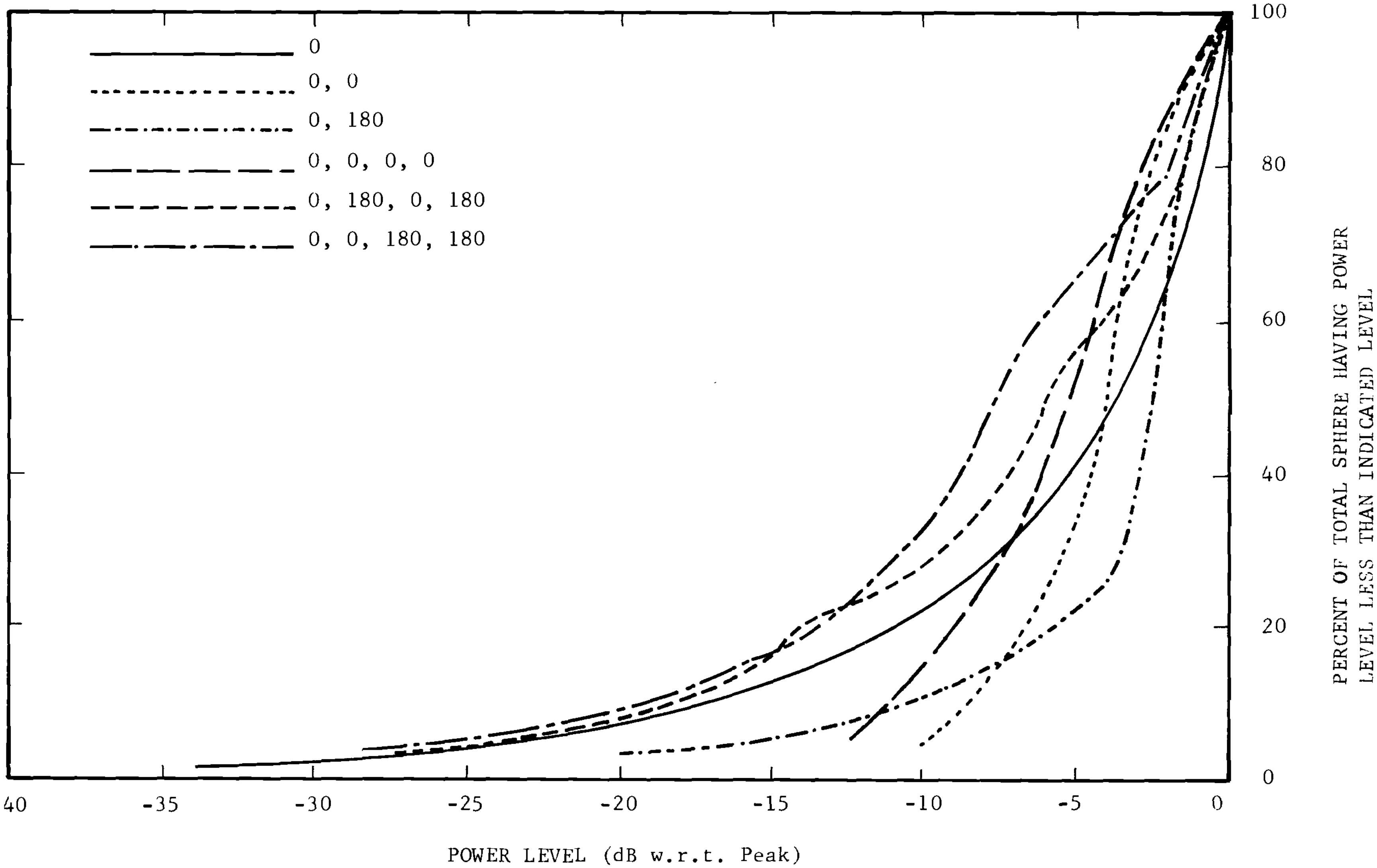


Figure 6. Calculated (using the scalar method) power coverage levels for several different 150-MHz arrays located on the SATRACK vehicle. The relative element phases for each array are as indicated.

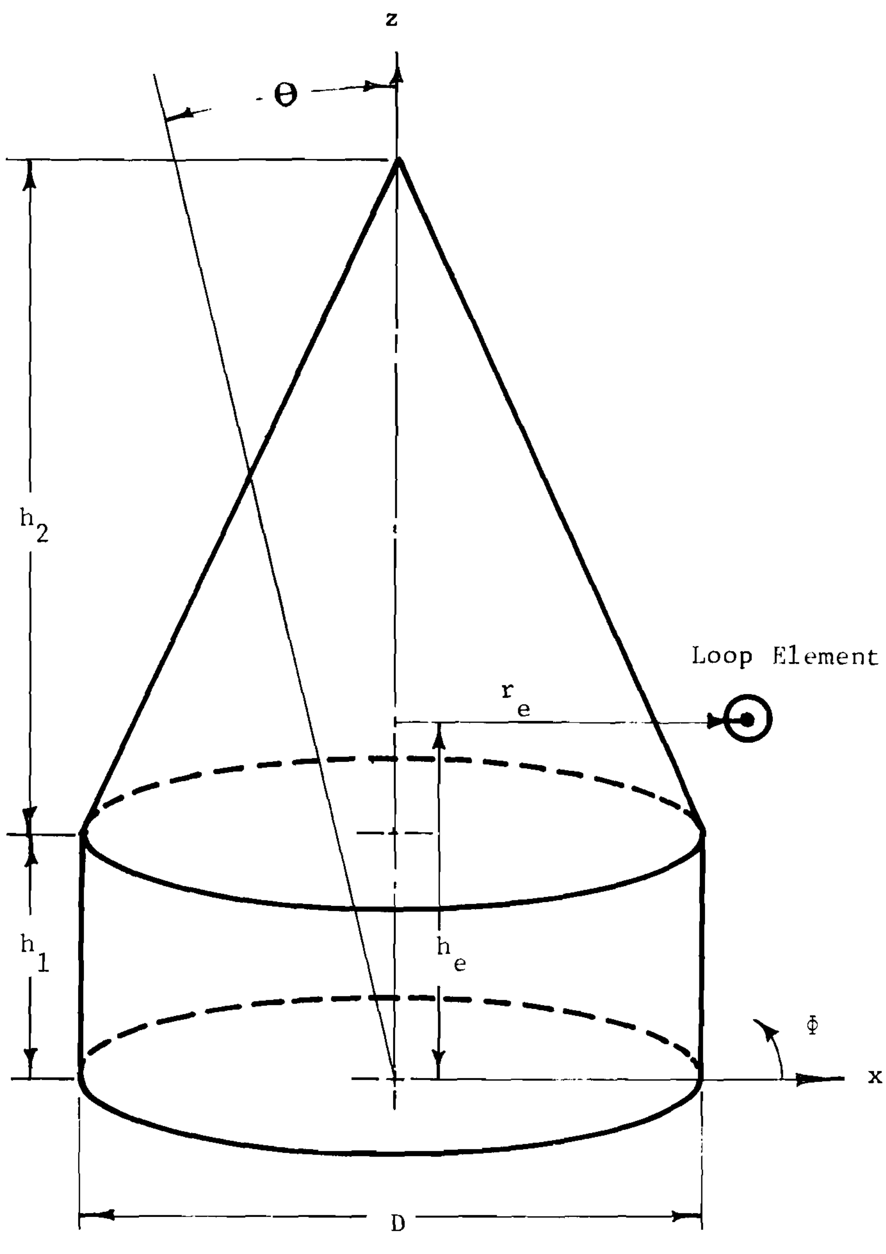


Figure 7. SATRACK geometry used in moment method calculations.

approximated by a 96 inches (2.44 meters) high cone having a diameter at the base of 72 inches (1.83 meters). Attached to the base of the cone is a 8 inch high (0.20 meter) right circular cylinder with a metal bottom. The surface of this cone/cylinder model of the vehicle was replaced by a grid of wires having the same shape, since such an approximation simplifies the application of the moment method.

A moment method evaluation of the wire radiating and scattering geometries has been formulated by Professor B. J. Strait of Syracuse University. A listing of this program was obtained and has been coded for the Univac U-1108 computer at Georgia Tech. Input and output data have been compared with those of Professor Strait and identical results were obtained.

The moment method computer program operates in the following fashion. First, a wire geometry is specified in terms of the location and size of the wire elements. Next the mutual impedances between the various portions of the wires are calculated in terms of an impedance matrix; then the impedance matrix is inverted to obtain the admittance matrix between the various portions of the wires. Specified input voltages are applied to those wires which are desired as radiators (i.e. the antenna elements) and then the currents induced in these wire elements as well as those induced in the rest of the structure are calculated. Using these currents the far-field pattern obtained from the composite structure is calculated.

Due to the nature of the computational technique, the antennas on the vehicle are modeled as wire radiators. These radiators are placed at predetermined points around the vehicle and the far-field pattern from the composite structure is calculated. The directivity and coverage levels may be obtained from the far-field pattern using the same subroutines described in the previous section. The effect of changing the antenna locations and/or type and the effect of in flight changes in the vehicle geometry on the antenna patterns may also be evaluated using this technique.

An electrically small loop antenna was used as the driven element in these calculations. Different numbers of these loops were placed around the vehicle at approximately 13 inches (0.33 meters) above the base of the right circular cylinder and at a distance of 37 inches (0.94 meters) from the axis of the cone cylinder.

Antenna patterns were calculated at 150 MHz for both two and four loops on the vehicle. The vehicle was represented by twelve equal angularly spaced wires running from the base of the cylinder to the tip of the cone. Loops were placed near the base of the cone and at equal angular increments around the base. The first loop was placed at $\Phi = 0^{\circ}$.

Figure 8 shows the pattern resulting from two loops placed 180° apart in space and fed in phase. The z-axis of the coordinate system coincides with the axis of the cylinder and the cone. The angle θ is the polar angle measured from the tip of the cone; the azimuthal angle Φ is measured from the first loop. Figure 8 shows equal intensity contours in 5 dB steps versus the roll angle Φ and pitch angle θ. All points having the same far-field intensity are connected together. For the two loop case, peaks of the pattern occur in the planes containing the z-axis and the loop. One peak occurs broadside to the vehicle while another occurs at about 30° from the tip of the cone and another at about 30° from the base of the cylinder.

Figure 9 shows a corresponding plot for four loops spaced 90° apart and all fed in phase. For the four loop case, peaks of the pattern occur halfway between the loops due to constructive phase addition. The directivity for the two loop case is 6.1 dB while it is 4.8 dB for the four loop case. Table II lists the coverage calculated with the two loop and four loop configurations, along with those measured by LMSC for their four-element, 150-MHz array. The calculated levels were normalized to a peak value equal to the calculated directivity and then reduced by 7.5 dB of assumed losses as was done by LMSC. In Table II it can be seen that the peak directivity is decreased in going from two elements to four elements; however, the coverage at low signal levels is improved. For example, the 90% coverage level is improved by 1.7 dB in going from two loops to four loops. It is also interesting to compare the four element calculations and measurements in this table. At the 90% level the difference is about 2.3 dB and at 95% coverage level the difference is only about 1.5 dB. This comparison indicates that the computer model is good especially at the higher coverage levels. A continuous plot of measured and predicted coverage levels is presented in Figure 10. From this figure it can be seen that the agreement between predicted and measured performance is quite good, especially at the higher signal levels. If circumferential wires had been used in the model in addition to the axial ones, better accuracy would have been obtained at the lower signal levels since a cross-polarized component would be generated. However, more

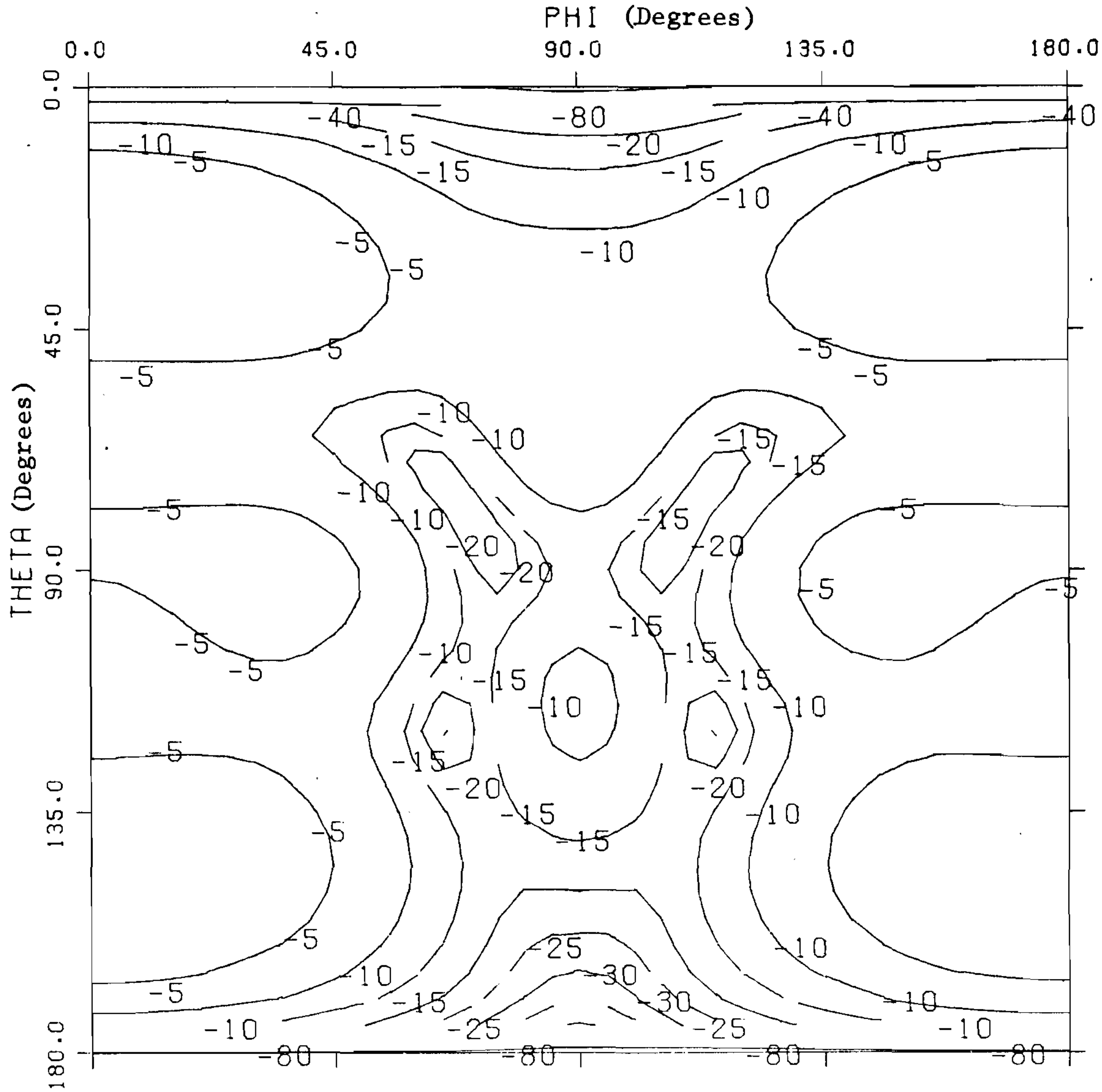


Figure 8. Equal intensity contour plot of radiation pattern data calculated (using moment methods) for two 150-MHz loop antennas located symmetrically on the SATRACK vehicle. Data is shown for only one-half of the sphere since the pattern is symmetric. Contour values shown are in dB below peak.

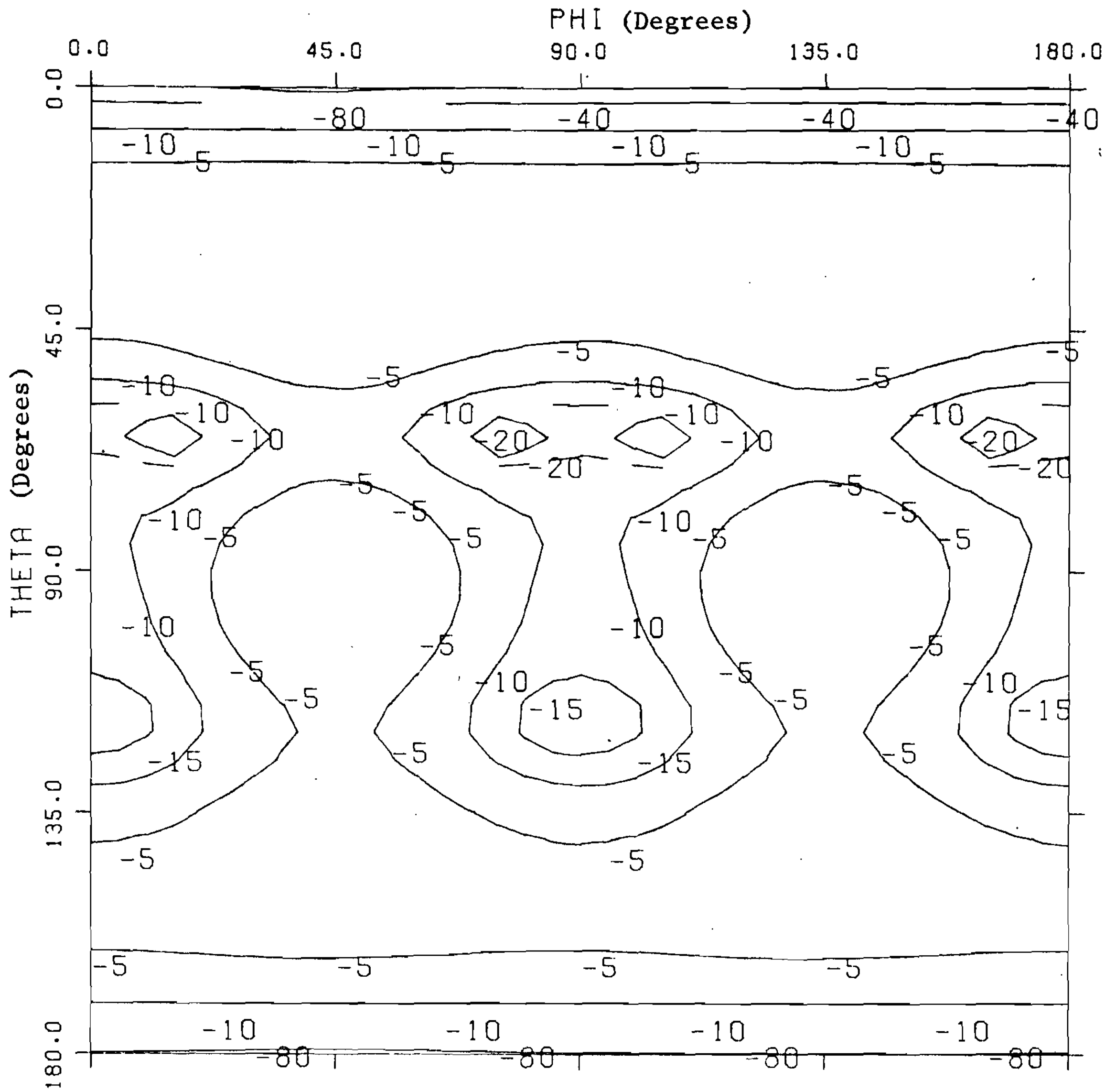


Figure 9. Equal intensity contour plot of radiation pattern data calculated (using moment methods) for four 150-MHz loop antennas located symmetrically on the SATRACK vehicle. Data is shown for only one-half of the sphere since the pattern is symmetric. Contour values shown are in dB below peak.

TABLE II

CALCULATED (MOMENT METHODS) AND MEASURED COVERAGE LEVELS FOR THE SATRACK ANTENNA SYSTEM OPERATING AT 150 MHz.

Antenna	Percent of the total sphere over which the power level (in dBi) is greater than or equal to the level indicated.				
	1%	50%	80%	90%	95%
2-Loop Calculation	-1.4	-7.9	-14.1	-18.1	-20.9
4-Loop Calculation	-2.7	-8.2	-13.2	-16.4	-18.6
4-Element Measurements	-1.9	-8.2	-11.6	-14.1	-17.1

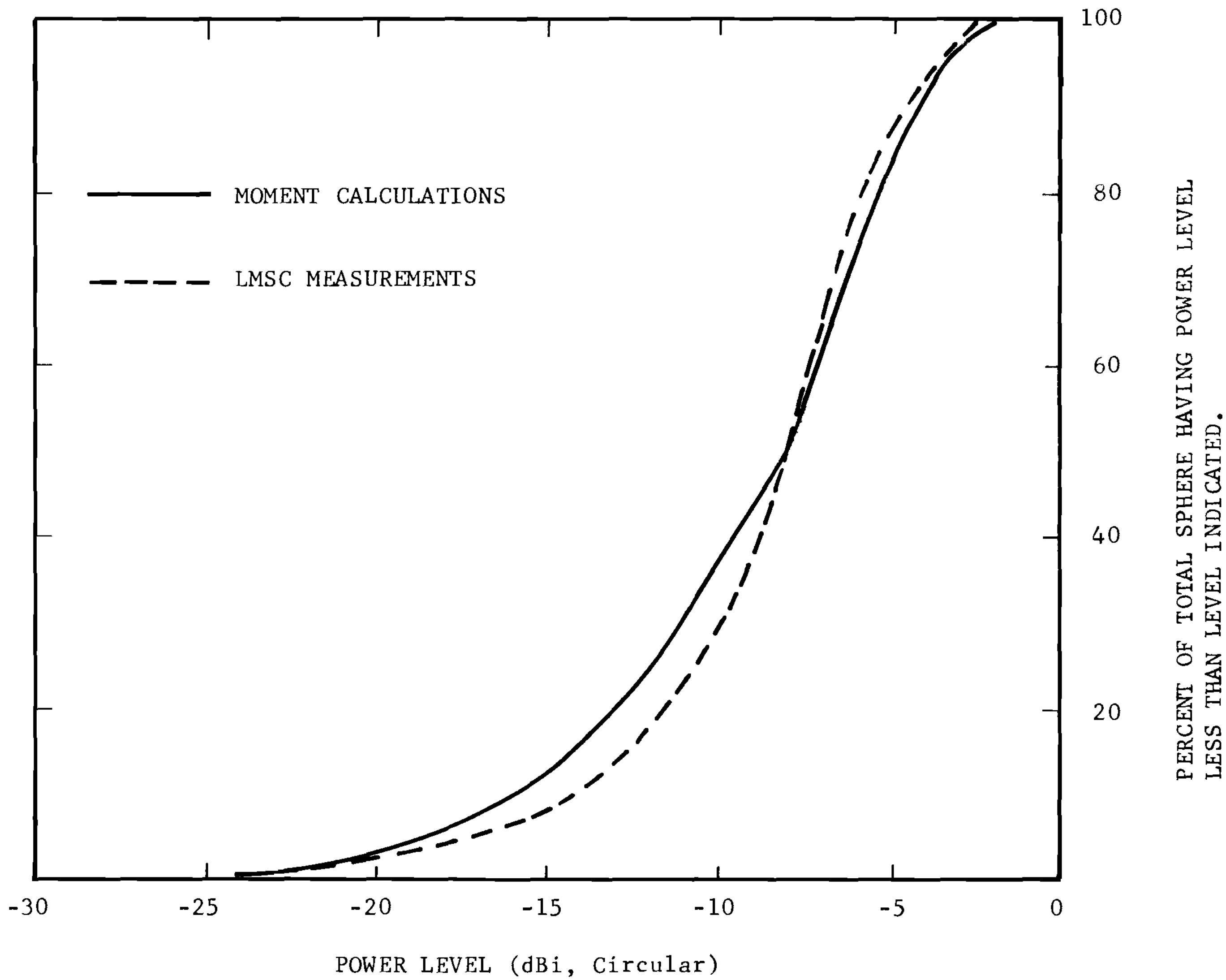


Figure 10. Comparison of percent coverage levels for the moment method calculations (solid) and LMSC (dashed) measurements at 150 MHz.

computer time would have been required to perform this calculation; therefore, it was not felt that the pursuit of this approach was warranted.

The analysis performed above indicates that the four-element,in-phase, 150 MHz design used by Lockheed can indeed provide the desired coverage. More importantly, however, the technique has been checked against measured data and has been proven to be a useful tool for accounting for vehicle effects in this complex geometry. This same method of calculation will be applied to the 400 MHz system in section IV.B.

C. Two-Element Analysis

As stated in the chronological outline of project events, the performance of the two-element 150-MHz antenna system was unsatisfactory to APL as of February 1974. Subsequent to that time, Lockheed improved that system by increasing the size of the elements to improve their efficiencies and therefore the 95% coverage levels. Lockheed had conducted pattern tests on these elements during Mid-April using arrays of two and four elements fed in phase. They observed that two antennas performed better than four.

Mr. Wade of LMSC forwarded a copy of the radiation distribution plot for the two element array to Georgia Tech to be analyzed. These numbers were fed into the computer manually and are plotted in three dimensional form in Figure 11. The peak directivity of this pattern was calculated to be 5.1 dBi. The peak of the pattern was normalized to the value specified by Lockheed (-4 dBi). Representative coverage levels derived from the Tech analysis are listed below.

COVERAGE LEVELS OF THE LMSC 150-MHz TWO-ELEMENT ARRAY

(The percentages shown indicate the percent of the total sphere over which the gain in dBi is greater than or equal to the level indicated)

Peak Value (0%)	50%	80%	90%	95%	Calculated Directivity
-4.0	-9.2	-14.0	-17.2	-20.7	5.1

The difference between the calculated directivity and reported gain is 9 dB. If 3 dB of this can be reasonably attributed to polarization loss, then the

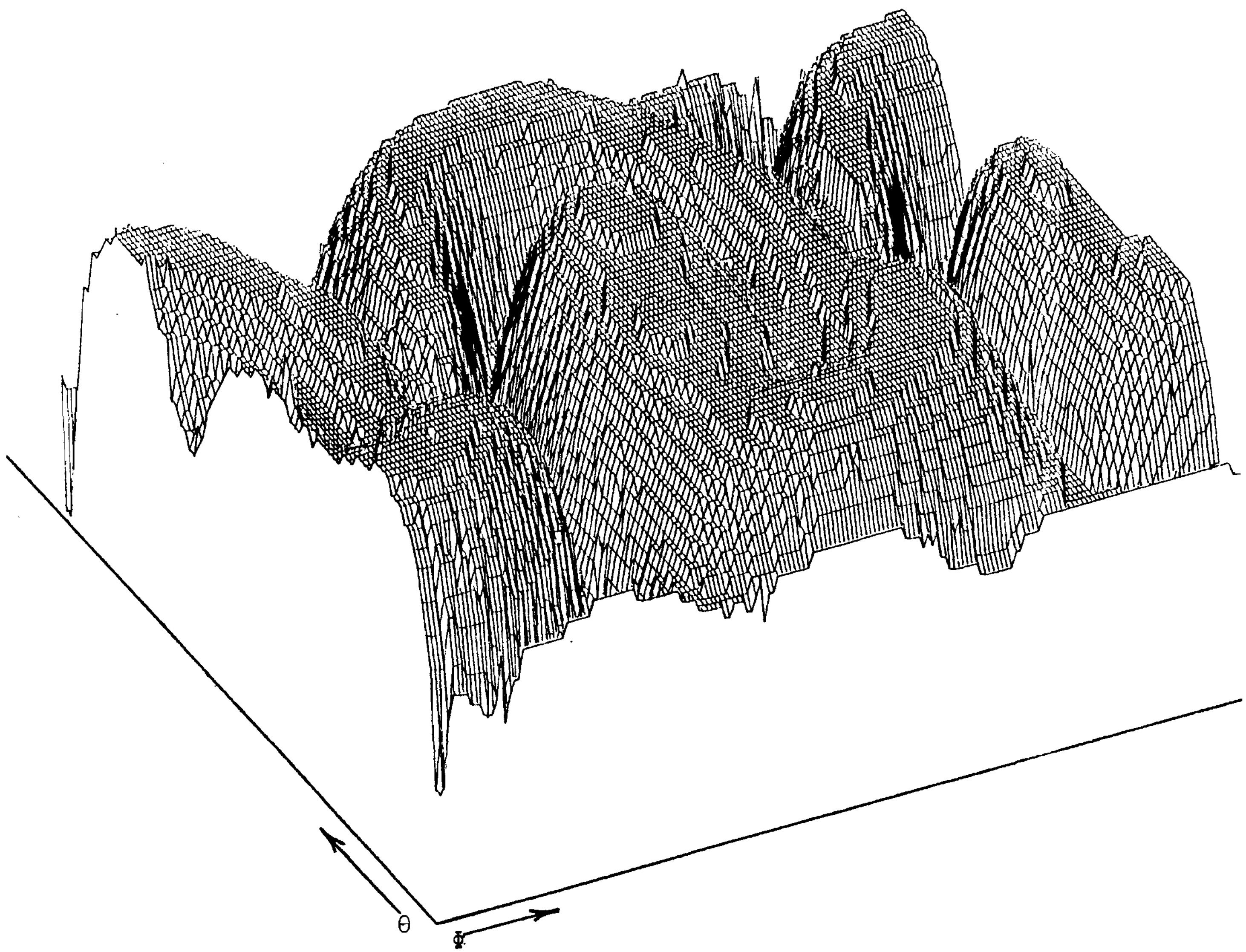


Figure 11. Three-dimensional rectangular plot of the 150 MHz two element array measured by LMSC.

other 6 dB must correspond to efficiency and cable loss. Evidently, Lockheed personnel did not feel that this design was satisfactory as they developed a new array of four blade-type antennas as discussed in the following paragraphs.

D. Four-Element Array

On 14 May 1974, Dr. D. G. Bodnar of Georgia Tech accompanied Dr. C. C. Kilgus of APL in a visit to LMSC facilities in Sunnyvale, California. At this time Lockheed personnel displayed data for a new 150-MHz antenna design which is superior in performance to either of the previous designs. The new antenna consists of an array of four tri-plate vanes (blades) each over a ten by fifteen inch ground plane. Over 90% of the sphere, the gain of this array was reported to be greater than -14.1 dB. Although this coverage is approximately 1 dB out of specification, it is significantly better than the previous design and was considered acceptable.

During this visit, Dr. Bodnar was able to obtain a contour plot and the associated punched paper tape of the radiation pattern from this new 150-MHz array. Firstly, a copy was made of this tape and forwarded to APL, and secondly, the data was analyzed on existing Georgia Tech computer programs to verify the LMSC directivity and coverage levels. The results of this Georgia Tech analysis were presented to APL in the form of a Special Technical Report on 5 June 1974. Significant findings of that analysis are also repeated in this section.

A copy of the four-element array radiation distribution plot furnished by Lockheed is shown in Figure 12. The peak value of the pattern is -2 dB (located in the vicinity of $\theta = 90^{\circ}$, $\Phi = 0^{\circ}$); however, this number is merely a relative one. The procedure used by Lockheed to determine the absolute value (w.r.t. a circularly-polarized isotropic source) is outlined below:

(1) Change the sign of all numbers in Figure 12,

(2) Calculate the directivity by integrating the pattern,

(3) Adjust the level of the entire pattern until the peak value corresponds to this directivity, and

(4) Subtract assumed polarization, efficiency, and cable losses from each point in the pattern.

Using the above procedure, an absolute level may be assigned to the pattern in Figure 12, and then it may be analyzed on the computer to determine the percent of the sphere that the power level lies above a certain level. The results of Lockheed's analysis which was furnished to Georgia Tech are

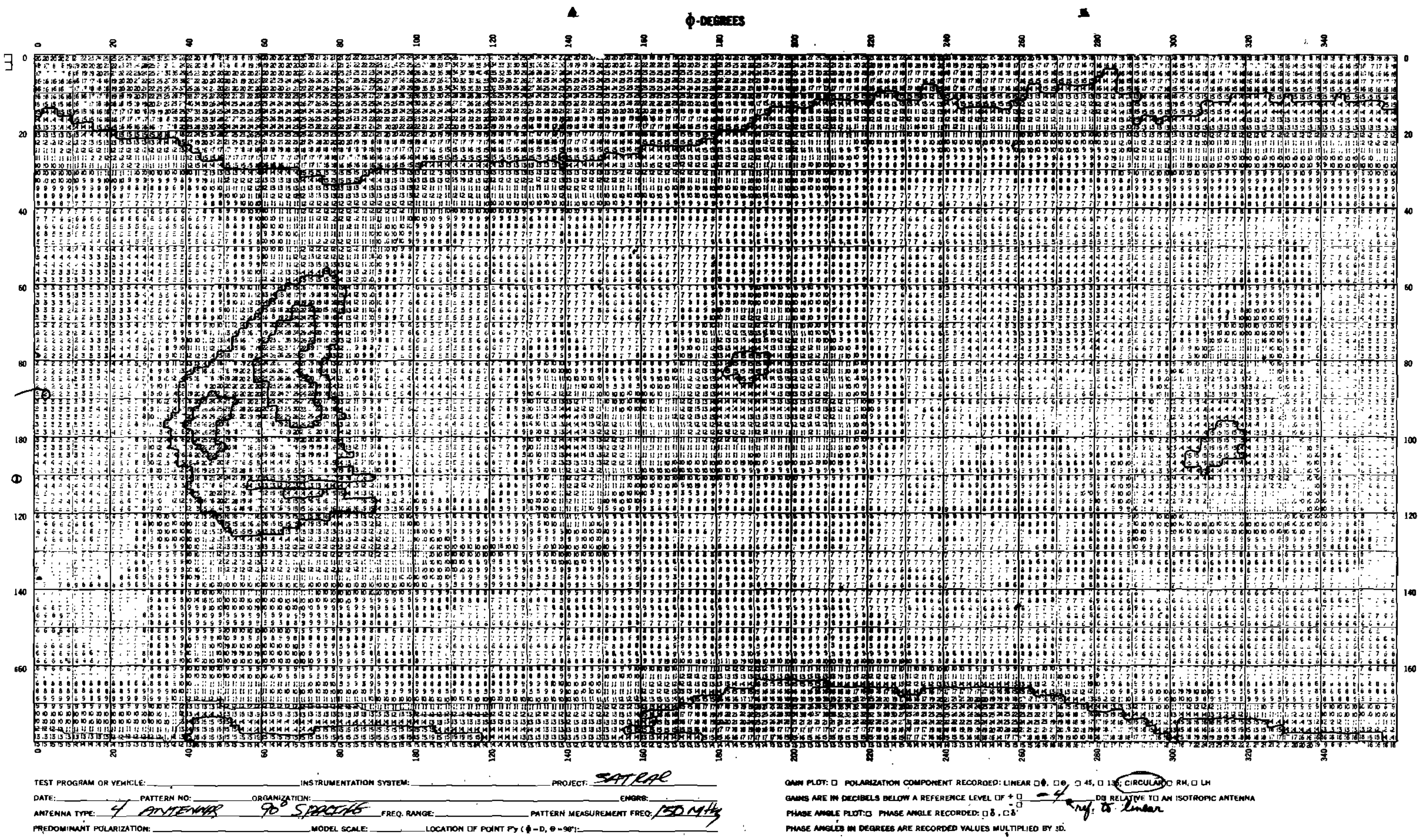


Figure 12. Radiation distribution plot for the four-element array operating at 150 MHz.

tabulated in Table III. The numbers in this table are normalized to the peak directivity. If the entries in this table are reduced by all losses (3 dB, 3.5 dB, and 1.0 dB for polarization, efficiency and cable, respectively), they may be plotted as percent coverage levels as illustrated by the dashed curve in Figure 13.

In addition to the radiation distribution plot and the numbers of Table III, Georgia Tech also obtained a punched paper tape containing the data in the distribution plot. The format of the data on this tape is indicated in Figure 14. One problem was immediately obvious once the tape was decoded--namely, the tape contained too much data. The vehicle positioner moves in steps of 2° in both azimuth and elevation; therefore, the tape should contain 90 rows (θ) with each row having 180 entries (Φ) as does the radiation distribution plot of Figure 12. The tape actually contained about 95 rows with 180 to 185 entries for each row. It was learned from LMSC personnel that this is a common problem due to the antenna range operator letting the positioning equipment run past the correct stop point for both the azimuth and elevation axes; Tech personnel were assured that taking the first 180 entries past the start-of-scan indicator for each of the first 90 rows would yield the correct data array. It was still uncertain as to which end of the paper tape corresponded to the start of the data, so two different arrays were formed. The first array was formed by reading from the outside end of the tape as it was furnished by LMSC and assuming that the first point corresponds to $\theta = 0^{\circ}$, $\Phi = 0^{\circ}$ (indicated by Figure 15 (a)). The second array was formed by reading the data from the other end of the tape and corresponds to the data block of Figure 15 (b). Each of these arrays was plotted in three-dimensional form so as to view any unusual aspects of the data as well as to get a general picture of the coverage holes. A 3-D plot of the data obtained by reading from the front end of the tape is shown in Figure 16.

The first thing that is immediately obvious from the plot is that the data contains a large number of "spikes" (both positive and negative). Lockheed is known to have encountered the same phenomenon but attributed it to a recording problem and edited the spikes out of the data. These spikes will have little effect on the calculated coverage levels unless one of them is the peak value. The validity of this statement is demonstrated by the directivity expression given by

TABLE III

PERCENTAGE COVERAGE LEVELS CALCULATED AND FURNISHED BY LOCKHEED FOR THE LMSC 150-MHZ FOUR-ELEMENT ARRAY. POLARIZATION, EFFICIENCY, AND CABLE LOSSES ARE NOT INCLUDED IN THIS TABLE.

Level No.	Level (dBi)	Percent of Sphere Having Power Greater than Level Indicated
1	+5.64	.00
2	+5.39	.23
3	+5.14	.76
4	+4.89	1.43
5	+4.64	2.10
6	+4.39	2.90
7	+4.14	4.05
8	+3.89	5.06
9	+3.64	6.08
10	+3.39	7.12
11	+3.14	8.29
12	+2.89	9.43
13	+2.64	10.37
14	+2.39	11.70
15	+2.14	13.53
16	+1.89	15.80
17	+1.64	17.80
18	+1.39	20.36
19	+1.14	23.43
20	+ .89	27.46
21	+ .64	30.07
22	+ .39	33.79
23	+ .14	38.59
24	- .11	42.64
25	- .36	46.39
26	- .61	49.34
27	- .86	52.28
28	-1.11	55.49
29	-1.36	57.77
30	-1.61	61.12
31	-1.86	63.96
32	-2.11	66.77
33	-2.36	68.56
34	-2.61	70.15
35	-2.86	71.97
36	-3.11	74.03
37	-3.36	75.56
38	-3.61	77.22
39	-3.86	79.02

Table III Continued

Level No.	Level (dBi)	Percent of Sphere Having Power Greater than Level Indicated
40	-4.11	80.44
41	-4.36	82.16
42	-4.61	82.90
43	-4.86	83.93
44	-5.11	85.04
45	-5.36	85.93
46	-5.61	86.68
47	-5.86	87.82
48	-6.11	88.74
49	-6.36	89.53
50	-6.61	90.12
51	-6.86	90.90
52	-7.11	91.55
53	-7.36	91.86
54	-7.61	92.39
55	-7.86	92.91
56	-8.11	93.33
57	-8.36	93.56
58	-8.61	93.79
59	-8.86	94.26
60	-9.11	94.64
61	-9.36	94.81
62	-9.61	95.05
63	-9.86	95.26
64	-10.11	95.51
65	-10.36	95.68
66	-10.61	95.88
67	-10.86	96.03
68	-11.11	96.24
69	-11.36	96.34
70	-11.61	96.51
71	-11.86	96.66
72	-12.11	96.80
73	-12.36	96.97
74	-12.61	97.15
75	-12.86	97.30
76	-13.11	97.46
77	-13.36	97.54
78	-13.61	97.68
79	-13.86	97.84
80	-14.11	97.90
81	-14.36	98.03
82	-14.61	98.10
83	-14.86	98.20
84	-15.11	98.37
85	-15.36	98.44
86	-15.61	98.53
87	-15.86	98.67
88	-16.11	98.77
89	-16.36	98.88
90	-16.61	98.94

Table III Continued

Level No.	Level (dBi)	Percent of Sphere Having Power Greater Level Indicated
91	-16.86	99.04
92	-17.11	99.09
93	-17.36	99.13
94	-17.61	99.21
95	-17.86	99.25
96	-18.11	99.28
97	-18.36	99.33
98	-18.61	99.37
99	-18.86	99.44
100	-19.11	99.51
101	-19.36	99.53
102	-19.61	99.55
103	-19.86	99.61
104	-20.11	99.63
105	-20.36	99.67
106	-20.61	99.67
107	-20.86	99.71
108	-21.11	99.74
109	-21.36	99.76
110	-21.61	99.79

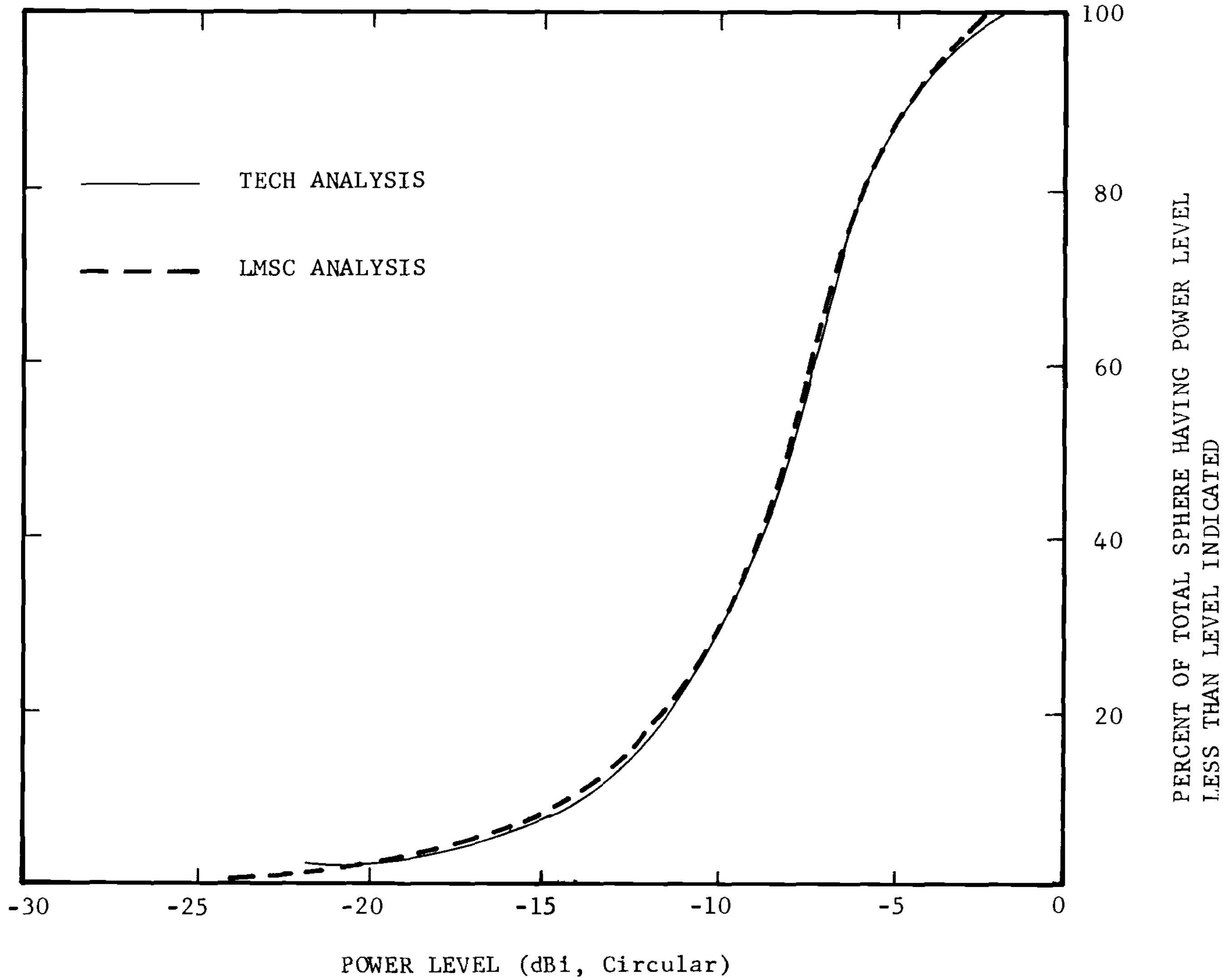


Figure 13. Comparison of LMSC and Georgia Tech analyses of the data measured on the 150-MHz four-element array.

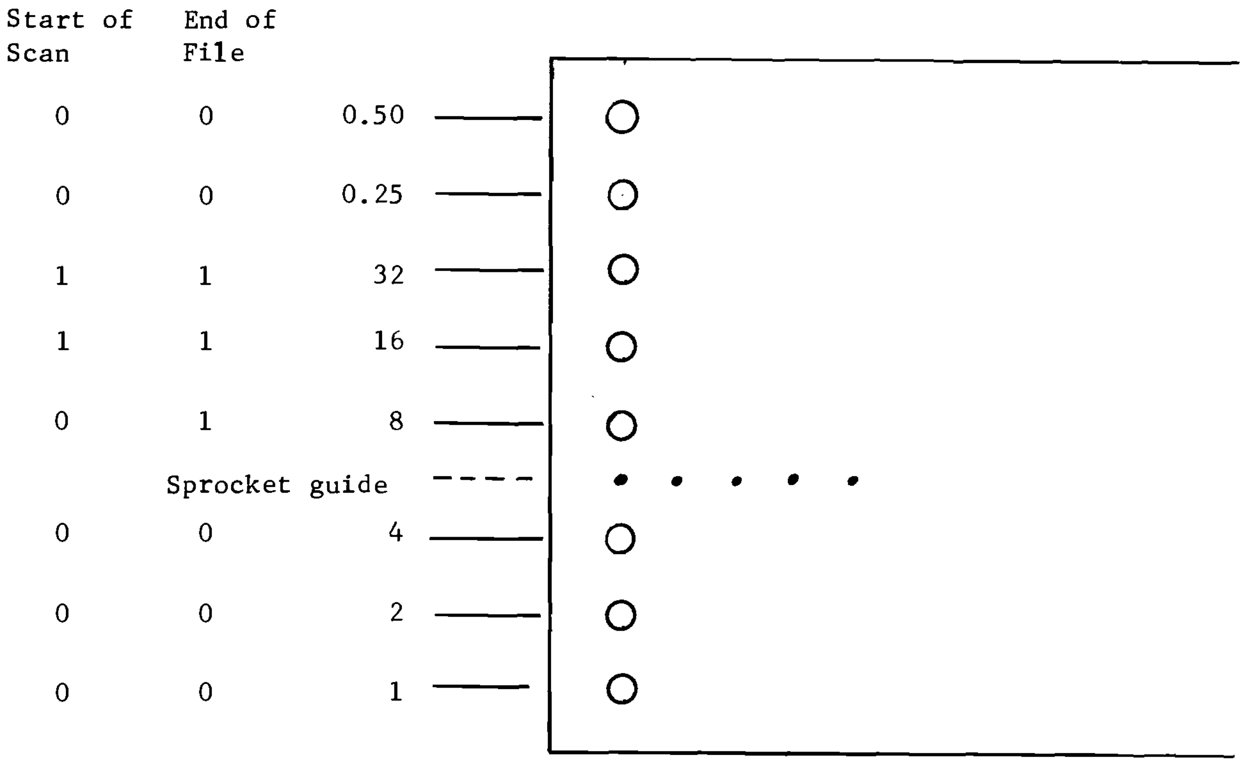
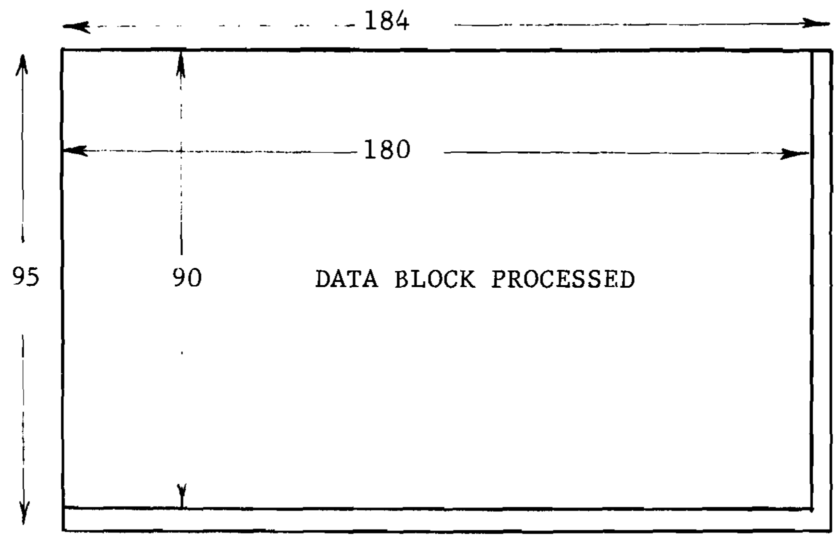
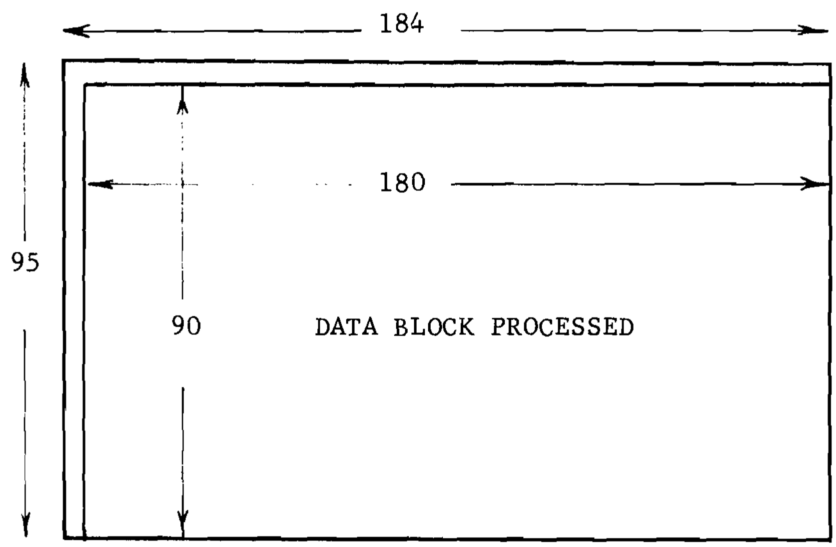


Figure 14. Diagram of radiation distribution data format on LMSC paper tape. The number printed by each line indicates the dB value associated with that line. The particular symbols for "Start of Scan" and "End of File" are indicated.



(a) Reading from front of tape



(a) Reading from rear of tape

Figure 15. Simplified diagram of data block processed illustrating differences which occur when a 90 by 180 point matrix of data is read from the (a) front and (b) rear of the LMSC punched tape.

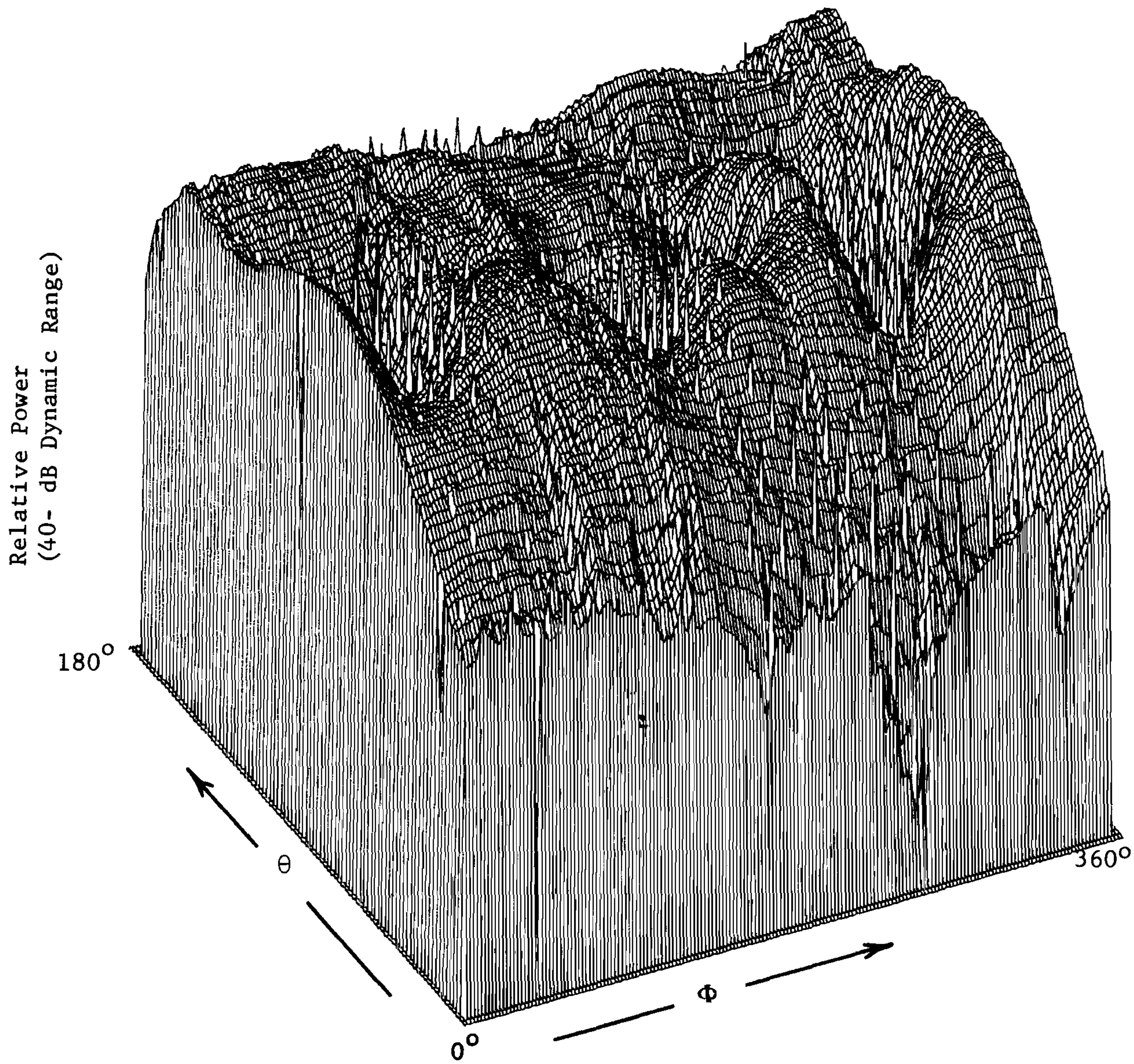


Figure 16. Rectangular three-dimensional plot of the data measured on the 150-MHz 4-element array when reading from the front of the tape.

$$D = \frac{4\pi P_{max}}{\Delta\theta \, \Delta\Phi \sum_i \sin \theta_i \left[\sum_j P(\theta_i, \Phi_j) \right]} \qquad (2)$$

where $P(\theta,\Phi)$ is the power pattern and P_{max} is the peak value of $P(\theta,\Phi)$. As shown in Eq. (2), the spikes are weighted by their area $\sin \theta \, \Delta\theta \, \Delta\Phi$ and contribute an insignificant amount to the summation unless, of course, one of them corresponds to P_{max}. In that case, the directivity and consequently all of the calculated coverage levels will be in error by an amount equal to the difference between the highest spike and the true peak. To ensure that this was indeed not the case, the location of the maximum values were found and the surrounding values were observed to be sure that the maximum value was not drastically different from the surrounding ones. Some of the spikes did reach the maximum value but none were above it; therefore, a high level of confidence can be assigned to the directivity calculated from Eq. (2).

The directivity and coverage levels for the data in each of the arrays of Figure 15 (a) and (b) were calculated by Georgia Tech and were found to be extremely close. The percent coverage levels for the array formed by reading from the front of the tape are plotted as the solid curve in Figure 13. Pertinent percentage levels from this plot are tabulated in Table IV and may be compared with the corresponding levels calculated by Lockheed.

A comparison of the numbers in Table IV indicates that the Georgia Tech and Lockheed analyses are quite close regardless of which end of the tape is read first. It is extremely important to note, however, that both analyses are based on assumed losses rather than an actual gain measurement. The efficiency and cable losses (3.5 dB and 1.0 dB, respectively) are indeed reasonable, and it is understandable that a gain measurement is unwieldy and time consuming; however, the data cannot be given a high level of credibility on the final model until an actual reference substitution gain measurement is performed. If this performance can be duplicated in a quiet chamber with little reflections present on the final model, the performance is considered by Georgia Tech to be acceptable even though it is approximately 1 dB outside the specification.

TABLE IV

COMPARISON OF SELECTED COVERAGE LEVELS* FOR THE LMSC 150-MHz 4-ELEMENT ARRAY FOR THREE SEPARATE ANALYSES OF THE SAME DATA.

	Directivity	Peak Level	50%	80%	85%	90%	95%
Georgia Tech Analysis I (Reading front of tape)	5.77	-1.73	-7.9	-11.2	-12.3	-13.7	-16.5
Georgia Tech Analysis II (Reading rear of tape)	5.73	-1.77	-7.9	-11.3	-12.3	-13.7	-16.8
Independent Lockheed Analysis	5.64	-1.86	-8.2	-11.6	-12.6	-14.1	-17.1

*Levels are in dB w.r.t. a circularly-polarized isotropic source and include assumed polarization, efficiency, and cable losses.

E. Microstrip Antenna Breadboarding

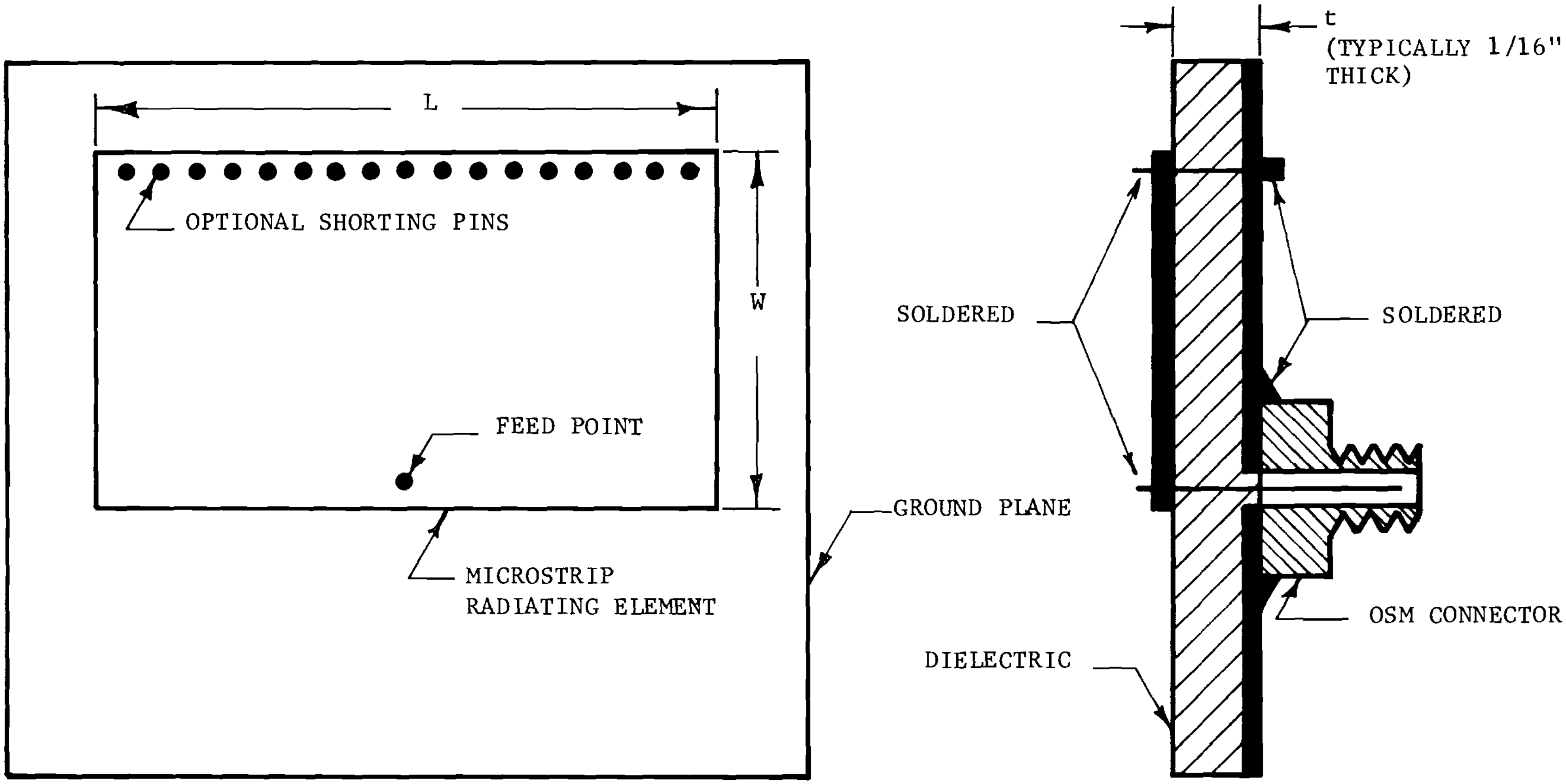
When it was learned that the performance of the various two-element arrays tested by LMSC were performing less than desired and that the improved four-element array was fairly large and space consuming, Georgia Tech initiated an effort to develop a microstrip patch radiator element. This element would probably not be significantly (if any) smaller than the LMSC blade over a ground plane, but it could result in a space savings if one element could operate at both 150 and 400 MHz. The antenna elements which were investigated both theoretically and experimentally are the microstrip patch radiators (see Figure 17) similar to the ones discussed by Munson [2] of Ball Brothers.

The instrumentation used to analyze the performance of this element is depicted in block diagram from in Figure 18. This set-up allows one to view the reflected power as a function of frequency across the band 50-500 MHz. The different points at which the structure under investigation resonates may be observed along with the effects of trimming, shorting, and otherwise altering the element. The X-Y recorder yields documented copies of any interesting data portrayed on the scope by transferring the signal to the recorder and manually sweeping the generator. The first element was a thin sheet of copper foil 92.7 cm(L) by 30.5 cm(W) bonded to the dielectric (fiberglass) of a 3 ft. by 4 ft. sheet of 1/16-inch thick printed circuit board. The element was fed from behind the ground plane as shown in Figure 17 and the output was not shorted. The structure was found to resonate at the following six frequencies:

(1) 160 MHz
(2) 240 MHz
(3) 290 MHz
(4) 319 MHz
(5) 403 MHz
(6) 481 MHz

when fed at the point shown in Figure 17. Although a definite resonance could be detected at these frequencies, the element appeared highly inefficient (VSWR between 5:1 and 10:1).

With the length (L) held constant at 92.7 cm, the width (W) was gradually trimmed in one cm increments from 30.5 cm down to about 14 cm. Frequencies (1), (4), and (6) above were virtually unchanged whereas frequencies (2), (3), and (5) varied inversely as the width (W). Specifically, the lowest frequency mode which depended on the width (i.e., frequency (2) above) always had a free-space quarter wavelength or more likely a



(a) TOP VIEW

(b) SIDE VIEW

Figure 17. Diagram of rear-fed microstrip antenna.

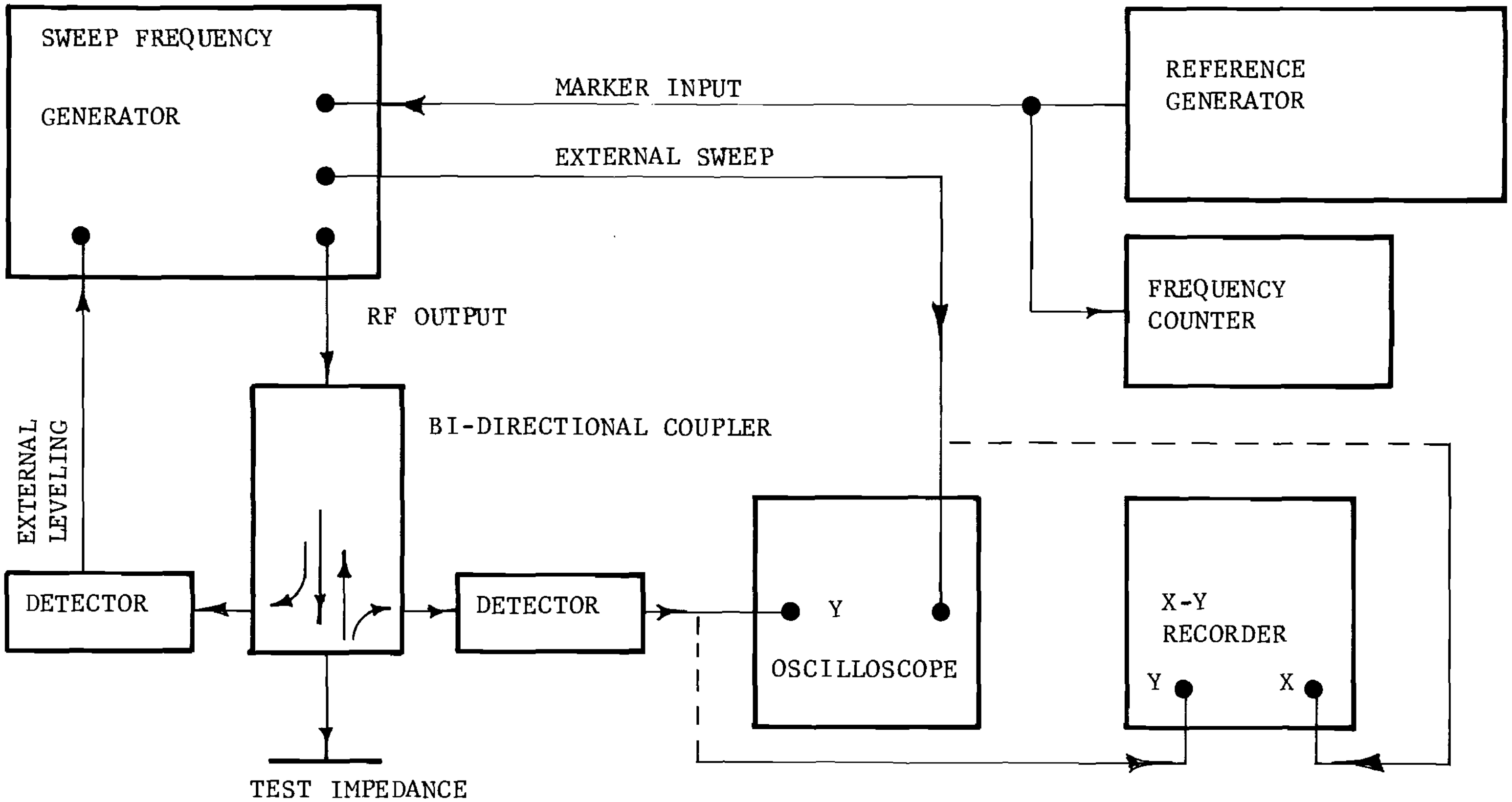


Figure 18. Schematic diagram of instrumentation used to perform and document broadband swept-frequency VSWR measurements.

dielectric half-wavelength equal to the width (W).

With the width held at 14 cm, the length (L) was incrementally shortened and the resonance frequencies observed. As one might expect, the antenna behaved like a dipole in this direction with resonances occurring at frequencies for which the antenna length was 0.5, 1.0, and 1.5 free-space wavelengths. The modes corresponding to these three lengths were the same ones which were unaffected by changes in width, namely (1), (4), and (6) above. VSWR's were still unacceptably high.

The next element investigated was identical to the previous one except that the long side opposite the feed point was shorted to the ground plane. With the width fixed at 14 cm, the length was trimmed in increments from an initial value of 81 cm down to a value of 38 cm. Modes were present which had free-space half wavelengths corresponding approximately to the length (L) as before, but new phenomena were also observed: (1) the VSWR of all modes decreased significantly (as good as 1.2:1 in some cases) and (2) a strange new mode appeared at 200 MHz and was unaffected by changes in length. However, when the width was successively trimmed from 14 to 13 and then to 12 cm, the frequency of this mode varied inversely as the width. The width (W) was found to correspond approximately to a quarter wavelength in the dielectric for this 200 MHz mode. This is theoretically plausible since the short circuit reflects an open circuit in parallel with the feed point impedance. The discovery of this resonance point was very encouraging since it implies that thin elements can be built at the SATRACK frequencies and in sizes small enough to place on the vehicle if the ground plane size can be reduced. The mode whose wavelength varied directly as the length (L) (approximately one-half wavelength) also exhibited some slight dependence on the width (W); consequently, this cross coupling must be considered when designing for two separate frequencies.

At this point, it was felt that enough was known of the theory of operation of the patch radiator to design an element which would oscillate at two independently controlled frequencies-- namely, 150 and 400 MHz. One element was then fabricated which consisted of a 10"(W) x 16"(L) patch of copper foil on a 3 ft. by 4 ft. sheet of printed-circuit board. The element which is similar to the one in Figure 17 had the side opposite the feed point shorted to the ground plane with a series of closely-spaced screws. A plot of the VSWR of this element as a function of frequency over the range 50-500 MHz is shown in Figure 19. The element had

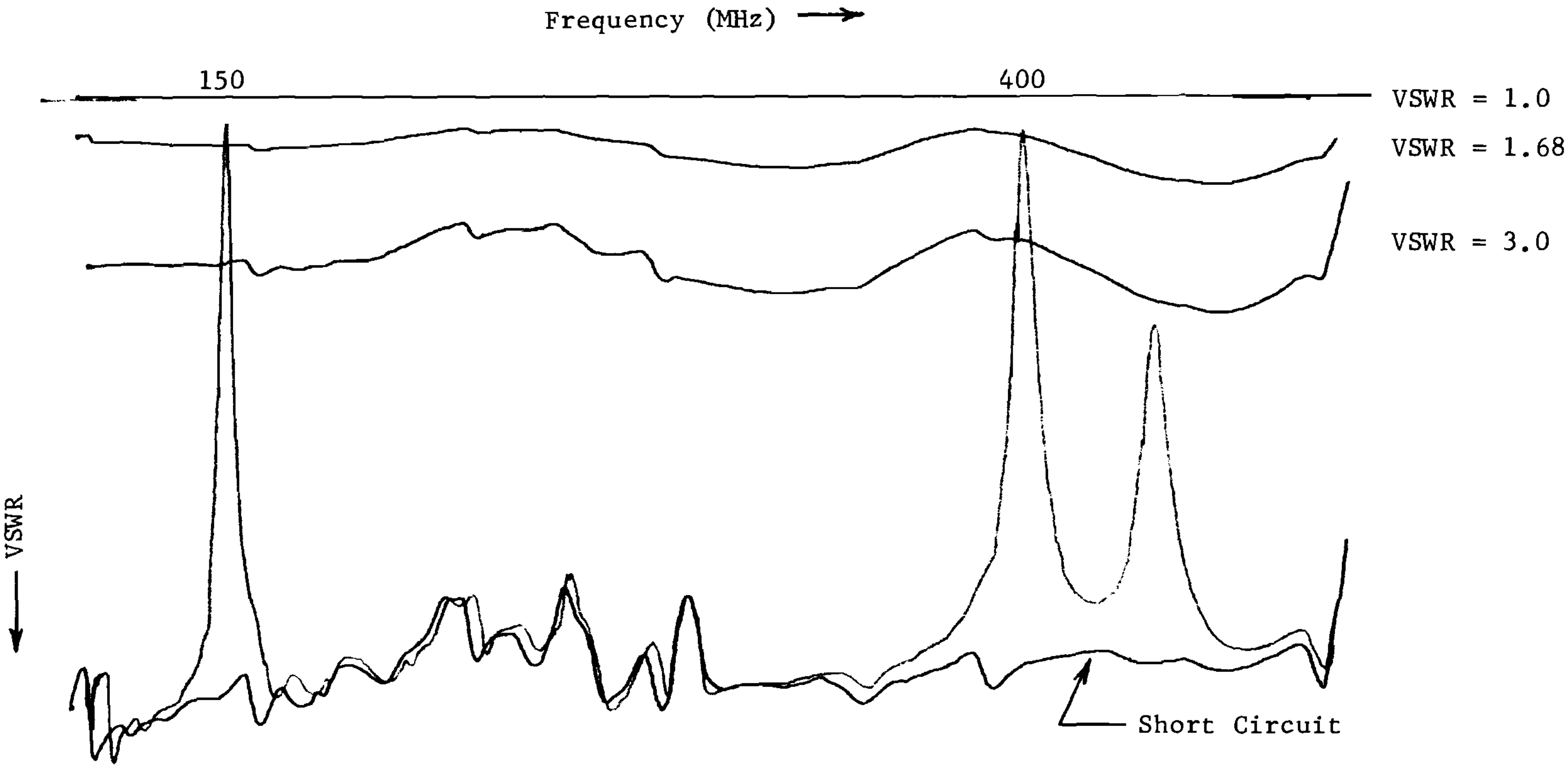


Figure 19. VSWR as a function of frequency for the patch radiator shown in Figure 17. Element is 10 inches by 16 inches and is positioned on a 3 ft. by 4 ft. sheet of 1/16-inch thick fiberglass coated PC board.

its lowest VSWR (approximately 1.5:1) at 150 and 400 MHz. Although the element is of a size that is easily carried on the vehicle, the associated ground plane is much too large. Consequently, the ground plane was trimmed away in 4 cm steps until the ground plane was the same size as the element. No noticeable degradation of performance was detected as the ground plane was shortened to the size of the element. The entire antenna structure was then 10" x 16" x 1/16".

The implications of these results of these experiments can best be summarized as follows.

(1) The antennas are extremely thin (1/16-inch) and lightweight,

(2) The low VSWR's for such electrically small antennas are encouraging, and

(3) The possibility exists for designing one structure which resonates at two independently controlled frequencies having a common feed point, A low-loss diplexer would be used to combine the two signals onto one line.

This element produced bandwidths which were somewhat larger than those predicted by Munson's theory. In personal conversations with Mr. Munson of Ball Brothers Research Corporation and Dr. C. H. Walter of Ohio State University, Tech personnel learned that this increased bandwidth for this type of antenna is an indication of a lossy dielectric (fiberglass) and an accompanying loss in gain. It was learned shortly thereafter that the 150 MHz system would be supplanted by one compatible with GPS; consequently, the effort was terminated before less lossy dielectrics such as teflon could be obtained.

IV. 400-MHz STUDIES

The studies at 400 MHz consisted of scalar and moment method calculations to determine the number of elements required and a listing of candidate elements. The scalar analysis was performed because the moment technique computer program was not available until late in the contract period. A computer analysis of Lockheed data was not performed as the corresponding tapes were not available to Georgia Tech during this period.

A. Scalar Calculations

Far-field power patterns were calculated (using Eq (1)) for array of two, four, and eight elements fed in phase and with three different types of element patterns. The three element patterns, which are given by

$$E(\theta,\Phi) = \sqrt{(1 + \sin\theta)(1 + \cos\Phi)} \quad , \qquad (3)$$

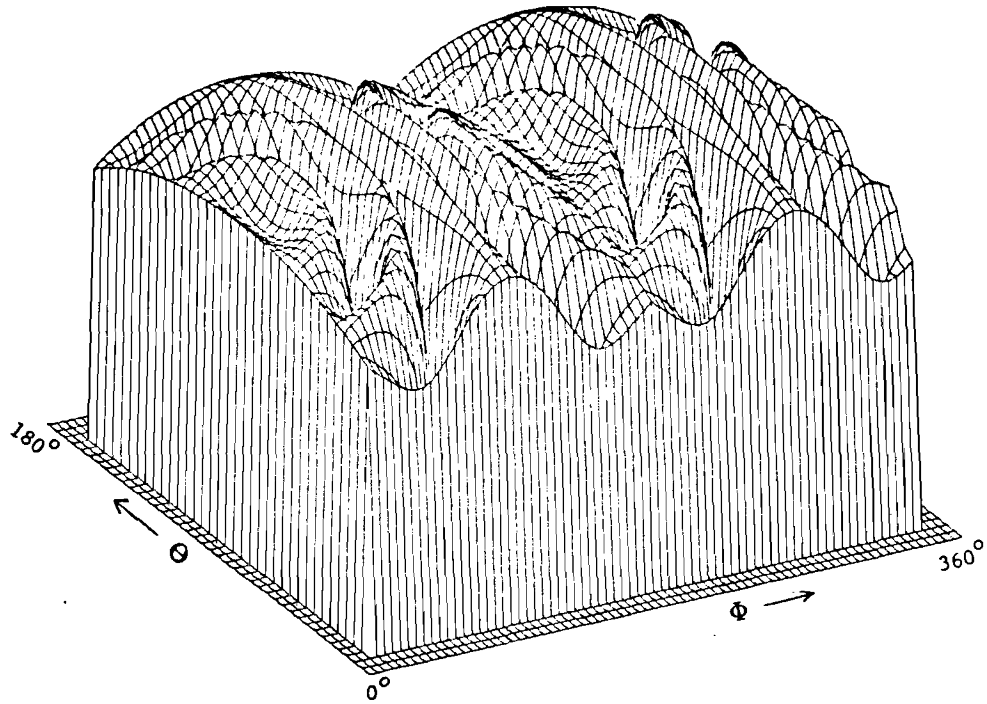
$$E(\theta,\Phi) = (1 + \sin\theta)(1 + \cos\Phi) \quad , \qquad (4)$$

$$E(\theta,\Phi) = 1.0 \quad , \qquad (5)$$

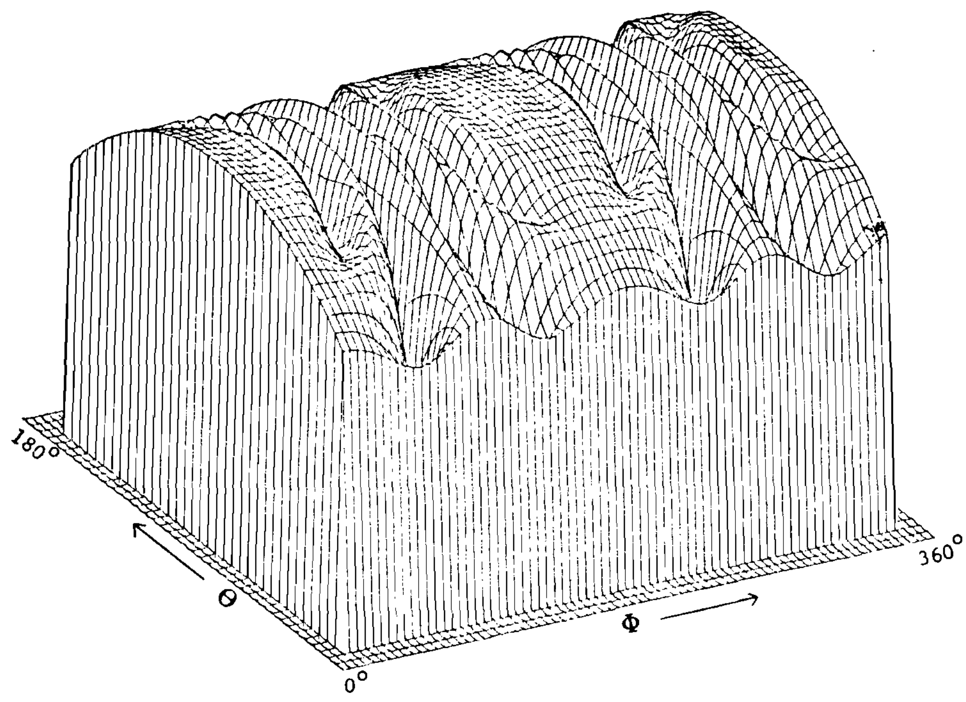
were included to determine the relationship between element pattern, the number of elements, and coverage obtainable.

Three dimensional radiation patterns for the two-element array having element patterns given by Eqs. (3) and (4) are shown in Figures 20 (a) and (b), respectively. Corresponding patterns for the four-element array with the same element patterns are shown in Figures 21 (a) and (b).

The percent coverage levels for the two, four, and eight element arrays were calculated and are plotted in Figures 22, 23, and 24, respectively. Significant coverage levels including the directivities shown and losses of 7.5 dB (3 dB polarization, 3.5 dB efficiency, 1 dB cable) are shown for all cases in Table V. Unfortunately, none of the arrays analyzed here were able to meet the required specification. This table may be summarized as follows: (1) both two and eight elements are better than four, and (2) for a given number of elements, coverage improves as the element pattern is tapered.

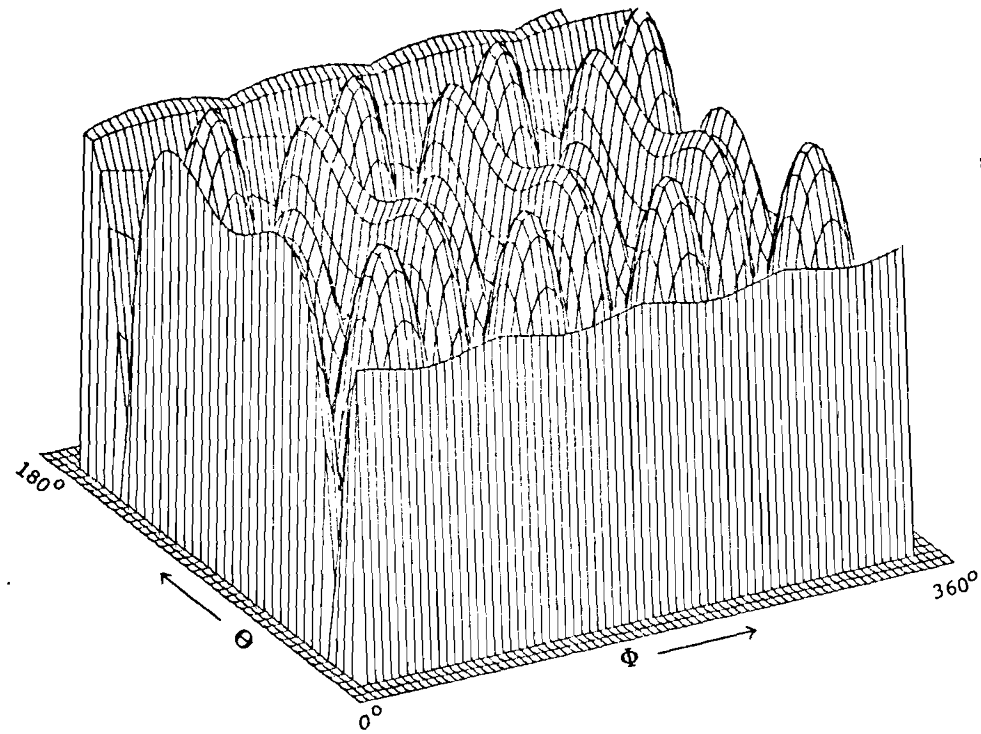


(a) Element Pattern, $E(\Theta,\Phi) = \sqrt{(1 + \sin\Theta)(1 + \cos\Phi)}$

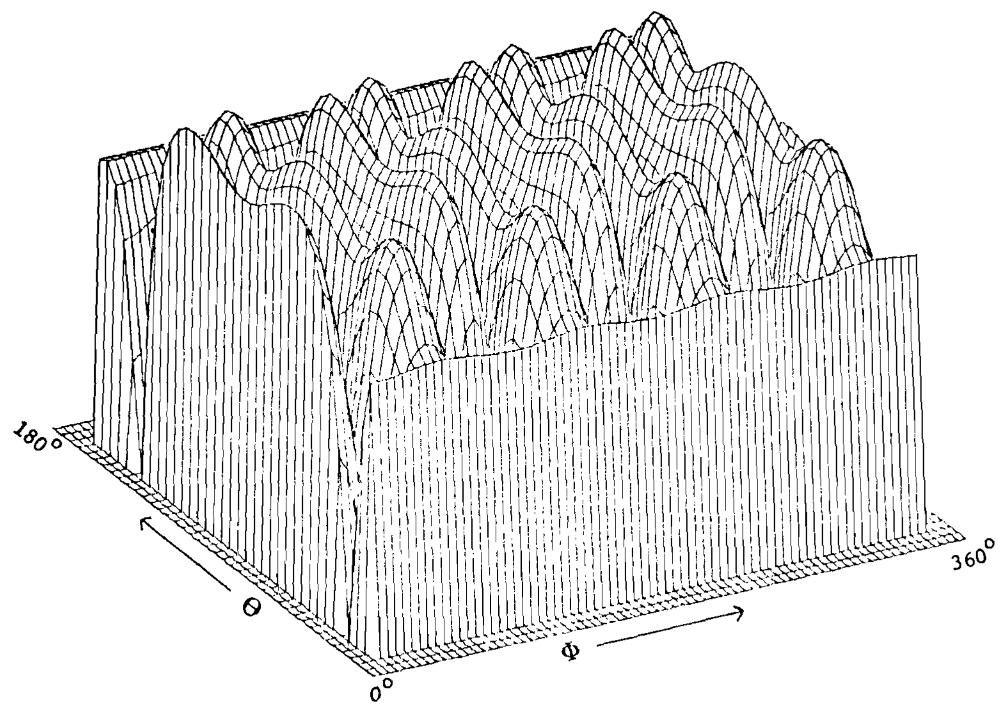


(b) Element Pattern, $E(\Theta,\Phi) = (1 + \sin\Theta)(1 + \cos\Phi)$

Figure 20. Calculated radiation patterns for the two-element circular array fed in phase and operating at 400 MHz. Element patterns are as indicated.



(a) Element Pattern, $E(\Theta,\Phi) = \sqrt{(1 + \sin\Theta)(1 + \cos\Phi)}$



(b) Element Pattern, $E(\Theta,\Phi) = (1 + \sin\Theta)(1 + \cos\Phi)$

Figure 21. Calculated radiation patterns for the four-element circular array fed in phase and operating at 400 MHz. Element Patterns are as indicated.

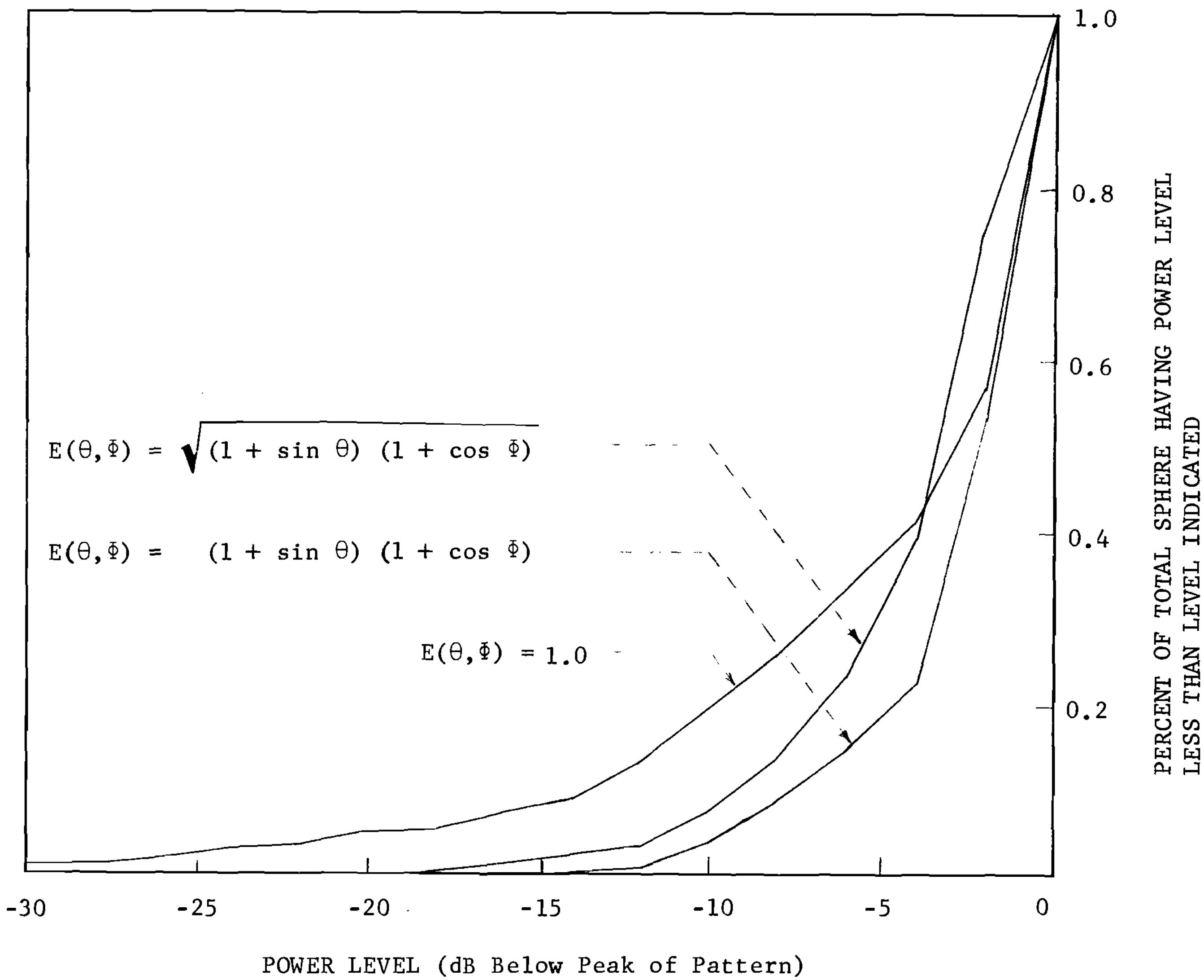


Figure 22. Calculated coverage levels for three different two-element arrays operating at 400 MHz and having the element pattern specified.

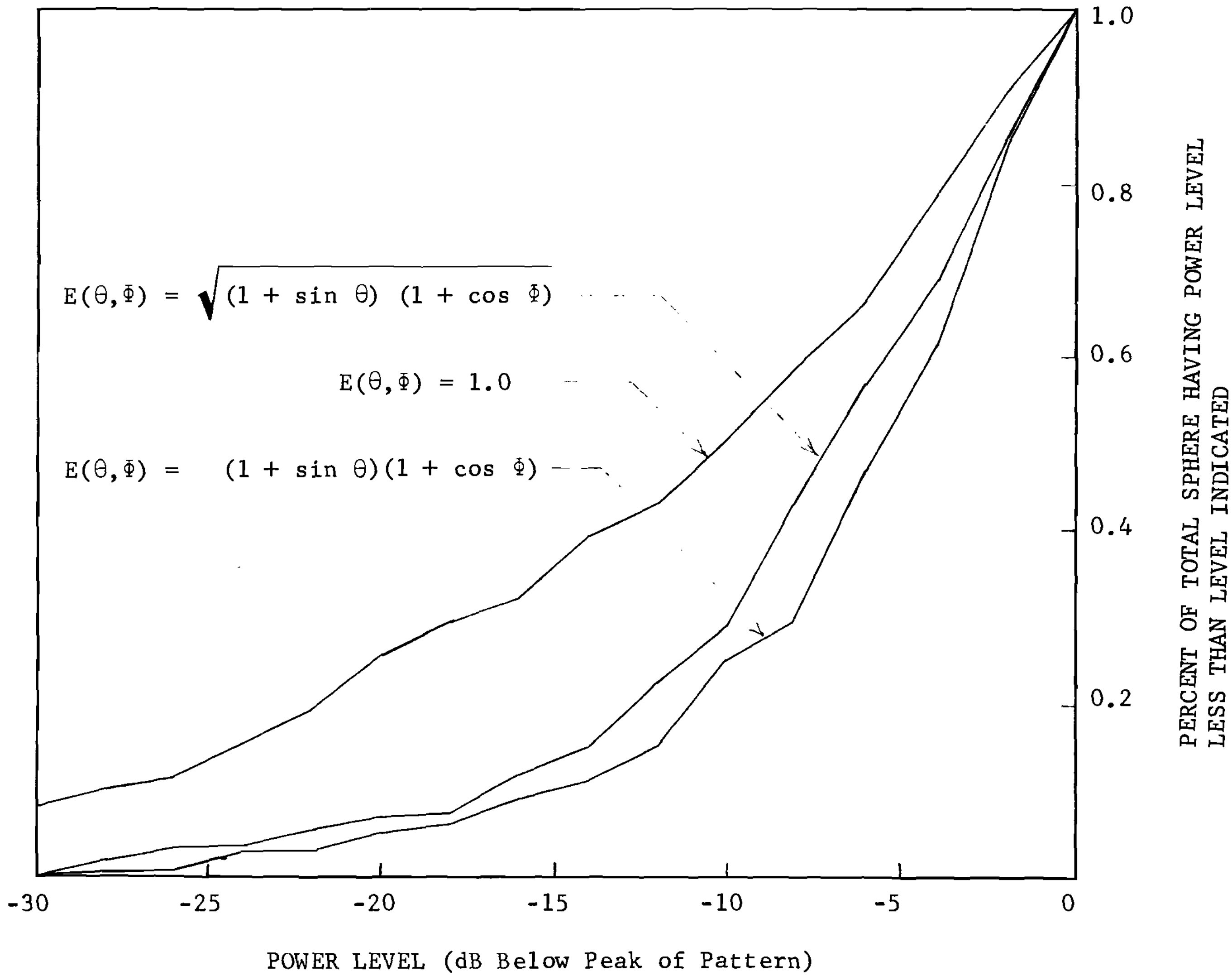


Figure 23. Calculated coverage levels for three different four-element arrays operating at 400 MHz and having the element pattern specified.

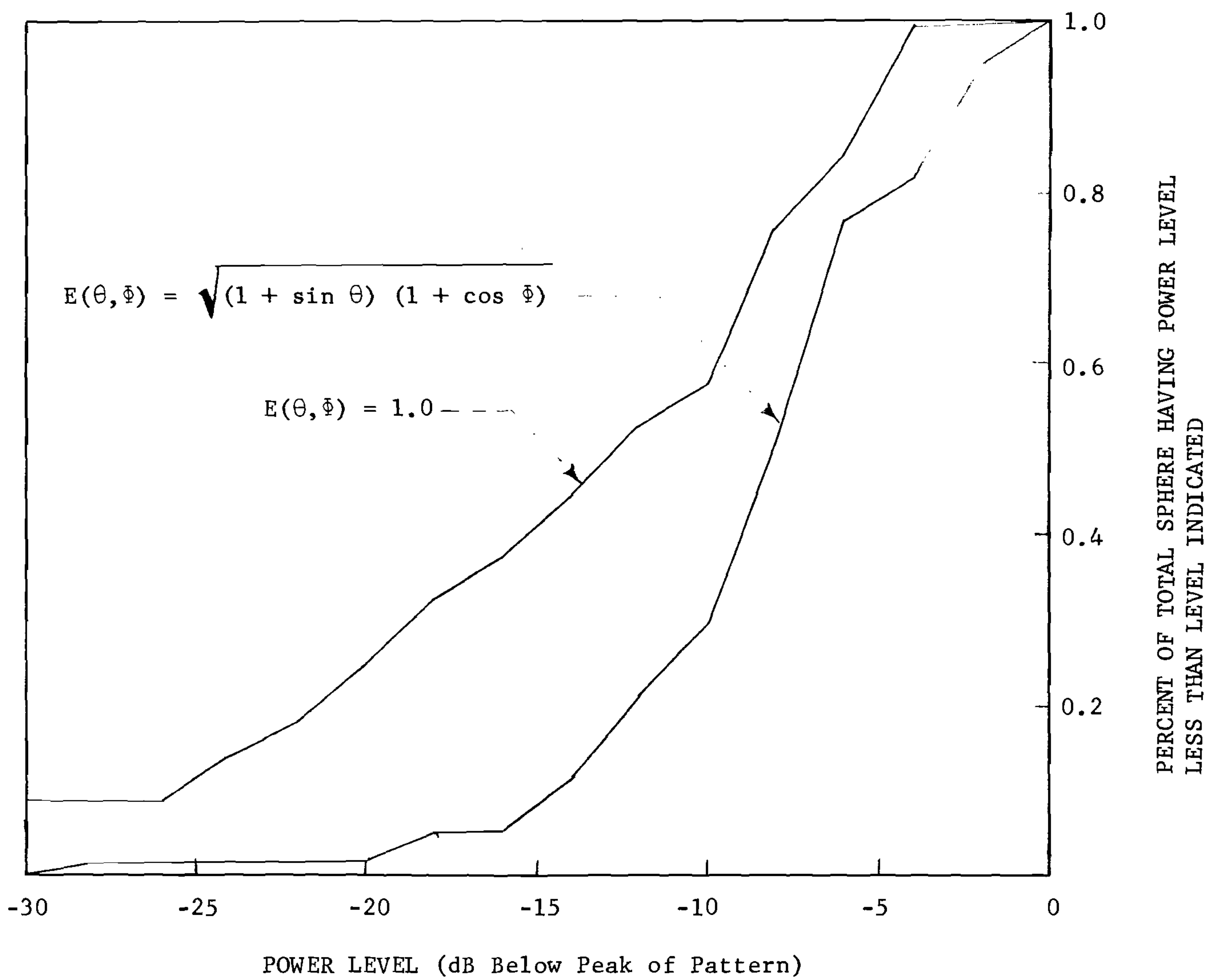


Figure 24. Calculated coverage levels for two different eight-element arrays operating at 400 MHz and having the element pattern specified.

TABLE V

CALCULATED COVERAGE LEVELS* FOR A CIRCULAR ARRAY OPERATING AT 400 MHz.

Element Pattern**	Directivity (dBi)	50% Level	80% Level	90% Level	95% Level
		TWO ELEMENTS			
#1	3.4	-7.5	-10.7	-13.3	-15.4
#2	2.9	-7.4	-14.4	-18.1	-24.6
#3	2.2	-7.5	-10.0	-12.8	-14.8
		FOUR ELEMENTS			
#1	5.4	-9.1	-14.8	-19.0	-24.6
#2	6.8	-10.9	-22.6	-28.7	***
#3	4.7	-8.4	-13.9	-17.8	-22.8
		EIGHT ELEMENTS			
#1	6.6	-8.9	-13.1	-15.4	-17.9
#2	9.8	-10.3	-19.2	-23.2	***

* Coverage numbers include 7.5 dB losses for polarization, efficiency, and cable.

** Element Patterns are identified as follows:

#1, $E(\theta,\Phi) = \sqrt{(1 + \sin\theta)(1 + \cos\Phi)}$

#2, $E(\theta,\Phi) = 1.0$

#3, $E(\theta,\Phi) = (1 + \sin\theta)(1 + \cos\Phi)$

*** Outside range of calculated numbers

As will be shown later in Section V, pattern calculations at 1600 MHz indicated that the circumferential element spacing should be on the order of every half wavelength in order to avoid a ripple in the roll plane ($\theta = 90^{o}$). If this scalar criteria and empirical rule are applied here, then about fifteen elements would be required at 400 MHz. It is felt that the use of a circularly polarized element with its inherent 3-dB coverage increase is far more attractive than going to a large number of elements.

B. Moment Method Calculations

Using the technique outlined in Section III.B, patterns were evaluated at 400 MHz for two, four, eight, and sixteen in-phase elements equally spaced around the SATRACK vehicle. Equal intensity contours for each of these configurations is presented in Figures 25 through 28. These figures show that as the number of elements is increased, the pattern ripple in the roll plane ($\theta = 90^{o}$) decreased. Using 16 elements the pattern is essentially independent of roll even though it depends on pitch. This uniformity of pattern in the roll plane agrees with the scalar 1600 MHz calculations reported in Section V.A.1. There a model was used in which the antenna pattern on the vehicle was assumed to be cardioid in shape and the field from the circular array was evaluated for various number of elements. At 1600 MHz, it was found that 64 elements were required to make the field pattern independent of roll angle in the $\theta = 90^{o}$ plane (this was the only plane in which the pattern was calculated). At 400 MHz one would anticipate that one quarter the number of elements (i.e.,16) would be required to produce similar results. This is indeed borne out by the pattern in Figure 28. The small variation of pattern with roll in Figure 28 is due to the fact that twelve wires were used to represent the vehicle instead of 16 as would be required by the number of elements.

A tabulation of pertinent statistical data on these configurations is presented in Table VI. An interesting result from this table is that even though the peak directivity of the configuration increases slightly as the number of loops is increased, the statistical behavior at the 90% level is not drastically affected by the increase in the number of elements. Hence, even though the patterns become more uniform in the roll plane, the dips in the pattern in pitch are sufficient to maintain an essentially constant coverage level independent of the number of elements that are used. If an efficiency (including polarization, element efficiency, and line losses) of -7.5 dB is assumed for each element as was done at 150 MHz, then a 90% coverage level

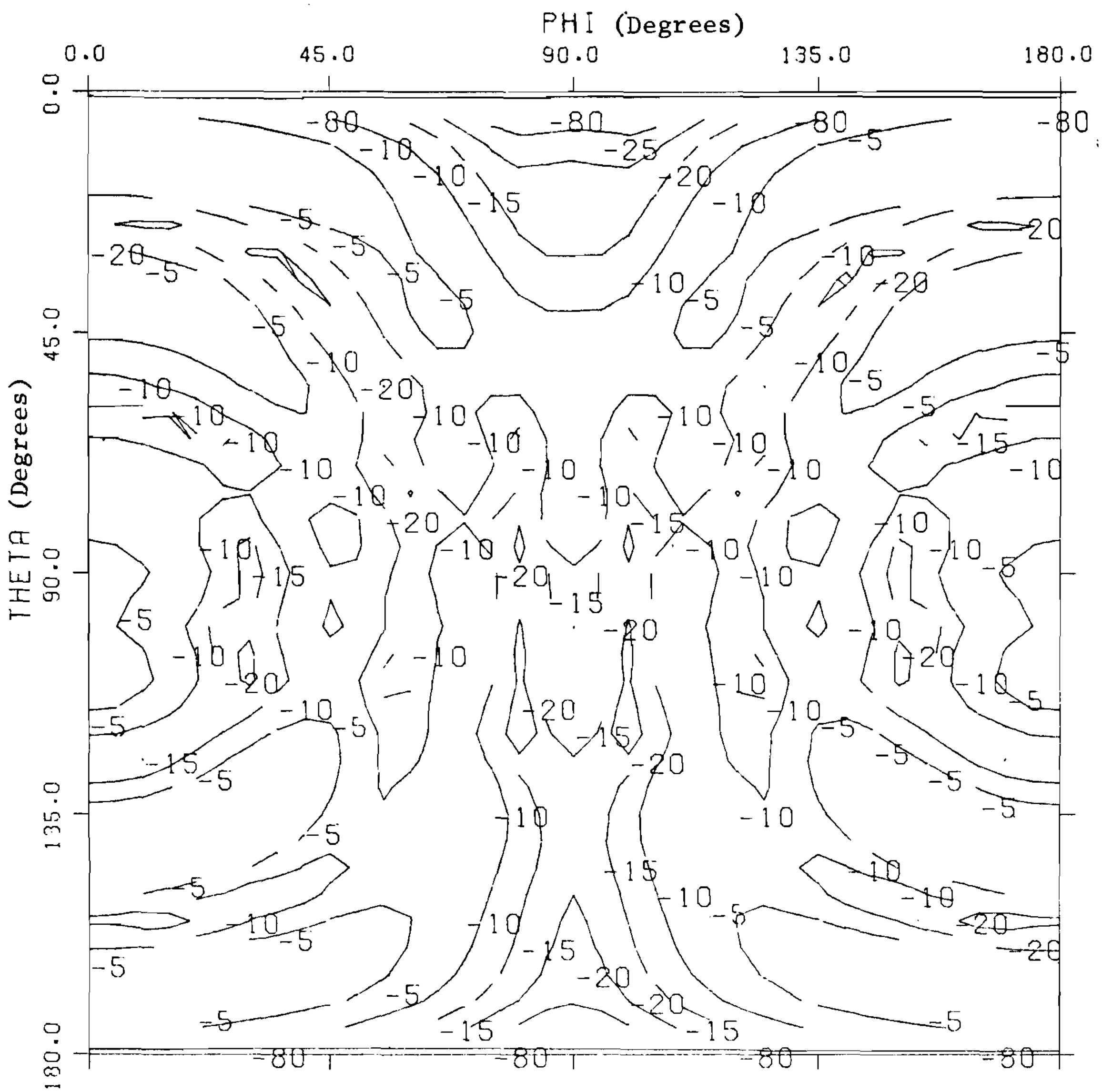


Figure 25. Equal intensity contour plot of radiation pattern data calculated (using moment methods) for two 400-MHz loop antennas located symmetrically on the SATRACK vehicle. Data is shown for only one-half of the sphere since the pattern is symmetric. Contour values shown are in dB below peak.

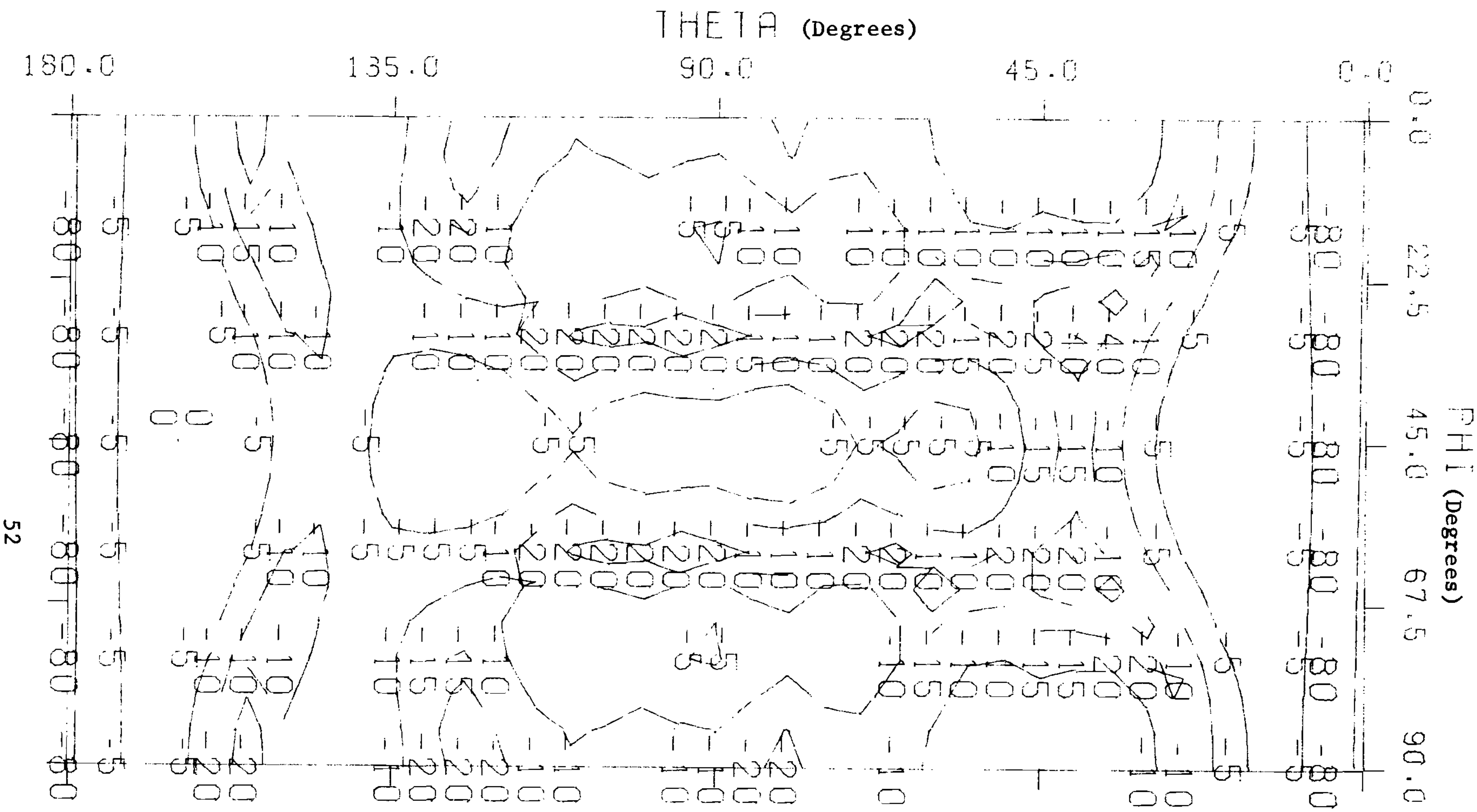


Figure 26. Equal intensity contour plot of radiation pattern data calculated (using moment methods) for four 400-MHz loop antennas located symmetrically on the SATRACK vehicle. Data is shown for only one-quarter of the sphere since the pattern is symmetric. Contour values shown are in dB below peak.

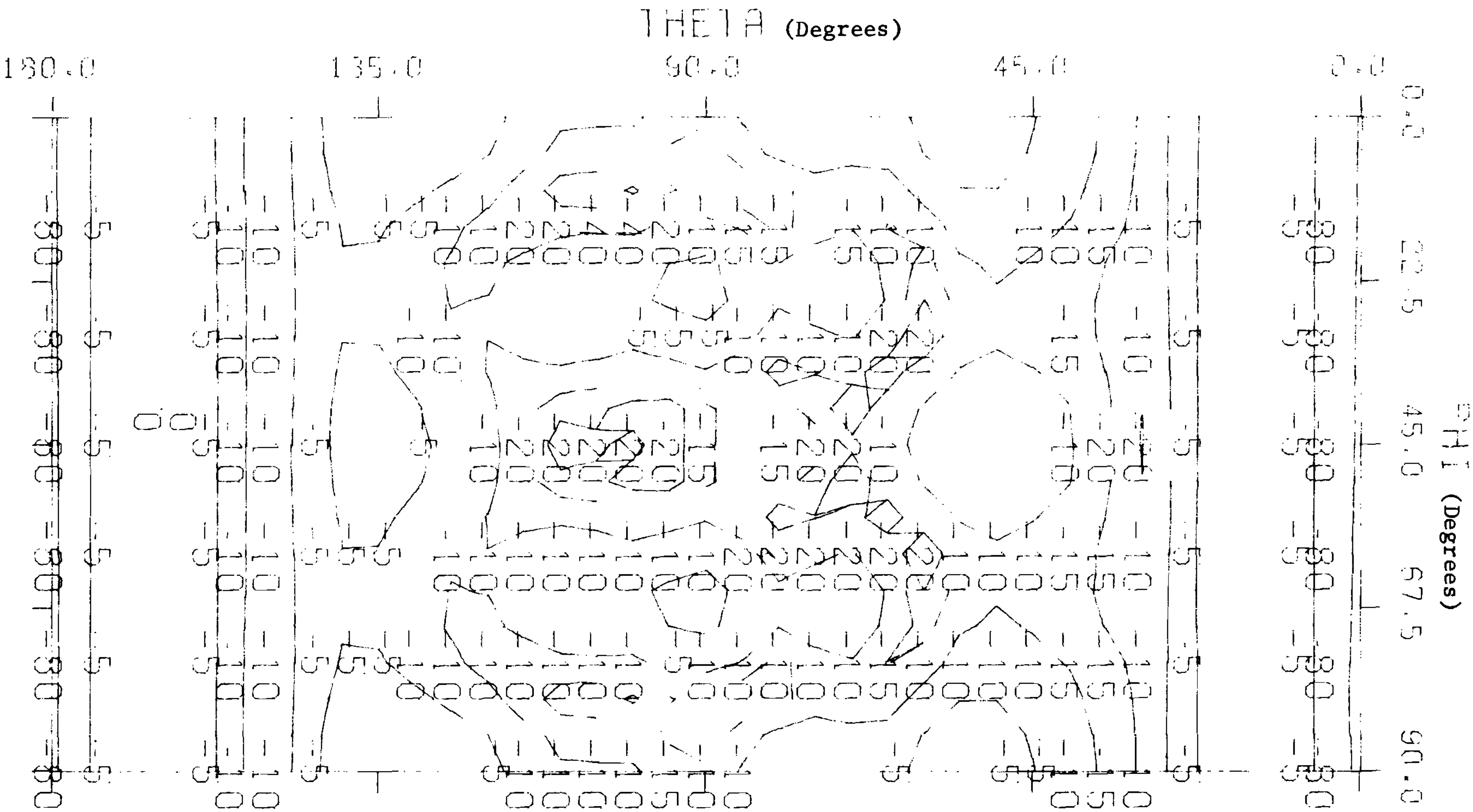


Figure 27. Equal intensity contour plot of radiation pattern data calculated (using moment methods) for eight 400-MHz loop antennas located symmetrically on the SATRACK vehicle. Data is shown for only one-quarter of the sphere since the pattern is symmetric. Contour values shown are in dB below peak.

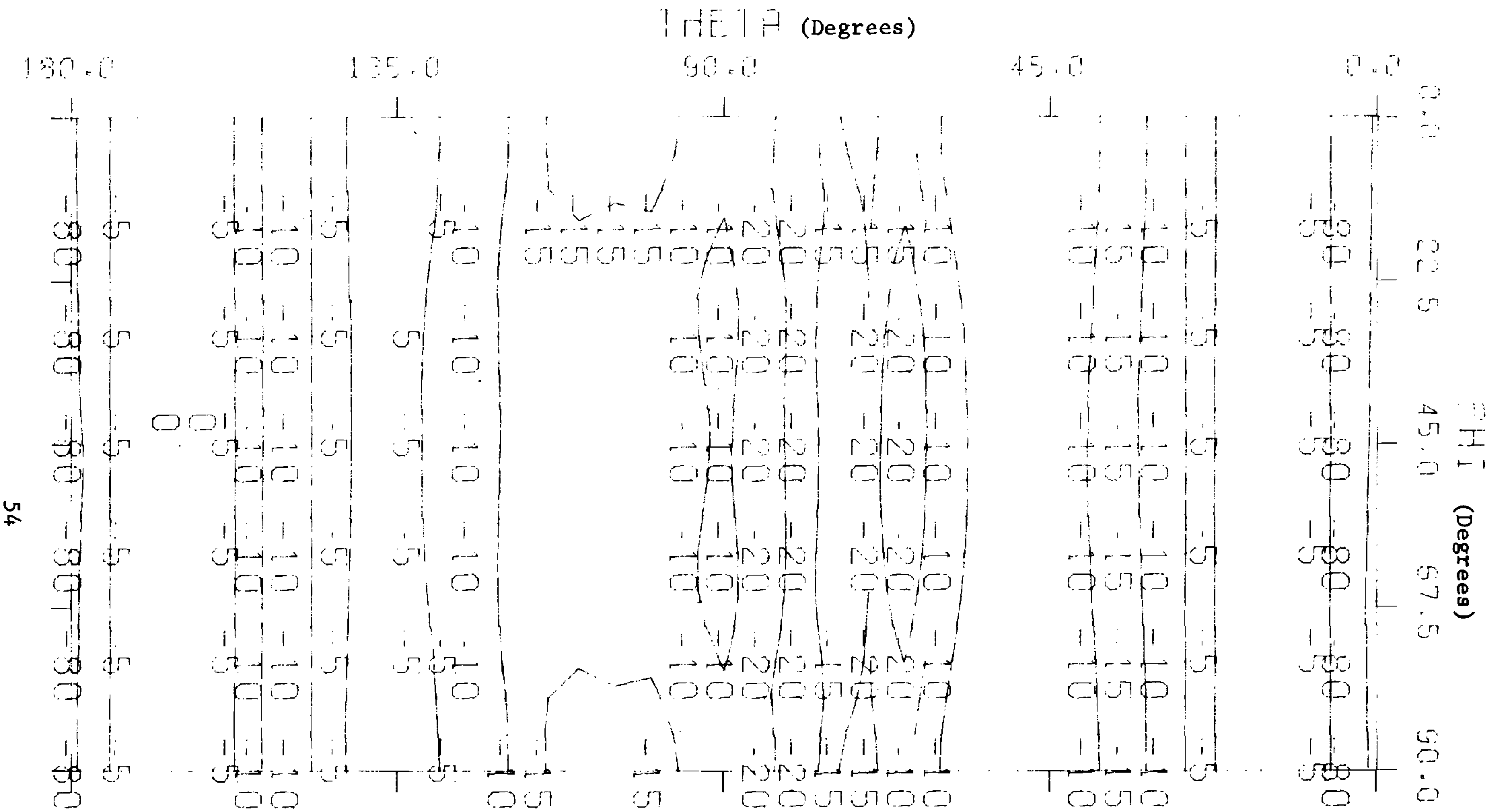


Figure 28. Equal intensity contour plot of radiation pattern data calculated (using moment methods) for sixteen 400-MHz loop antennas located symmetrically on the SATRACK vehicle. Data is shown for only one-quarter of the sphere since the pattern is symmetric. Contour values shown are in dB below peak.

TABLE VI

CALCULATED (MOMENT METHODS) COVERAGE LEVELS* OF SEVERAL DIFFERENT ARRAYS OF IN-PHASE LOOP ELEMENTS OPERATING AT 400 MHz ON THE SATRACK VEHICLE.

Number of Elements	Calculated Directivity	1%	50%	80%	90%	95%
2	6.9	-0.6	-8.9	-13.6	-17.6	-20.1
4	7.1	-0.4	-8.9	-14.2	-18.4	-22.9
8	7.3	-0.2	-9.2	-14.2	-17.7	-21.0
16	8.1	-0.6	-10.4	-14.9	-17.2	-23.3

* Percentages indicate the fraction of the total sphere having coverage (dB w.r.t. isotropic, circular) greater than or equal to the level specified. Polarization, efficiency, and component losses of 3.0, 3.5, and 1.0 dB, respectively, have been assumed.

of about -18.4 dBi is expected. From Figure 10 it is seen that the predictions may be as much as 2.5 dB pessimistic; hence, the 90% coverage level may be more like -16 dBi. This figure is well below the -10 dBi specification and presents a very real design problem to the SATRACK program. As stated previously, circular polarization now appears a necessity as a partial solution to the problem.

V. 1600-MHz STUDIES

It was learned in the latter part of June 1974 that the GPS frequency of 1600 MHz (actually near 1575 MHz) would definitely replace 150 MHz as one of the links between the satellite and the vehicle. At this time, Georgia Tech undertook the task of determining the most feasible antenna and the type of coverage to be expected at this new frequency. This situation was further complicated by the discovery that rapid or instantaneous changes in the phase of the far-field radiated field could degrade the total system performance.

The scalar as opposed to the moment method was used to calculate array patterns, since the large size of the vehicle in wavelengths and the large number of elements required would have required an excessive amount of computer time.

A. Scalar Calculations

The scalar approach at this frequency is identical to that used at 150 MHz (i.e., see Eq. (1) and Figure 1).

1. Amplitude Patterns

In an attempt to determine the number of elements required to eliminate pattern ripple in the roll plane ($\theta = 90^o$), scalar amplitude patterns were calculated in this plane for different numbers of array elements. In particular, patterns were calculated for 2, 4, 8, 16, 32, and 64 equally spaced cardioid elements, and the results are presented in Figures 29, 30, 31, 32, 33, and 34, respectively. As is obvious from these figures, the pattern approaches omnidirectional for a number of elements between 32 and 64.

2. Phase Patterns

LMSC and APL personnel, realizing that a large number of elements would be required to overcome the interferometer effect if the signals are added coherently, have suggested a four-element, two-channel, time diversity system. Using this technique, which is portrayed in Figure 35, two elements are spaced 180^o apart on the vehicle and are combined coherently in phase while two other elements are displaced 90^o from these two and also combined in phase but independently of the first two. The input to the translator is then switched periodically between these two channels. The receiver(s) on the ground then pick the larger of the two signals at any given time. The

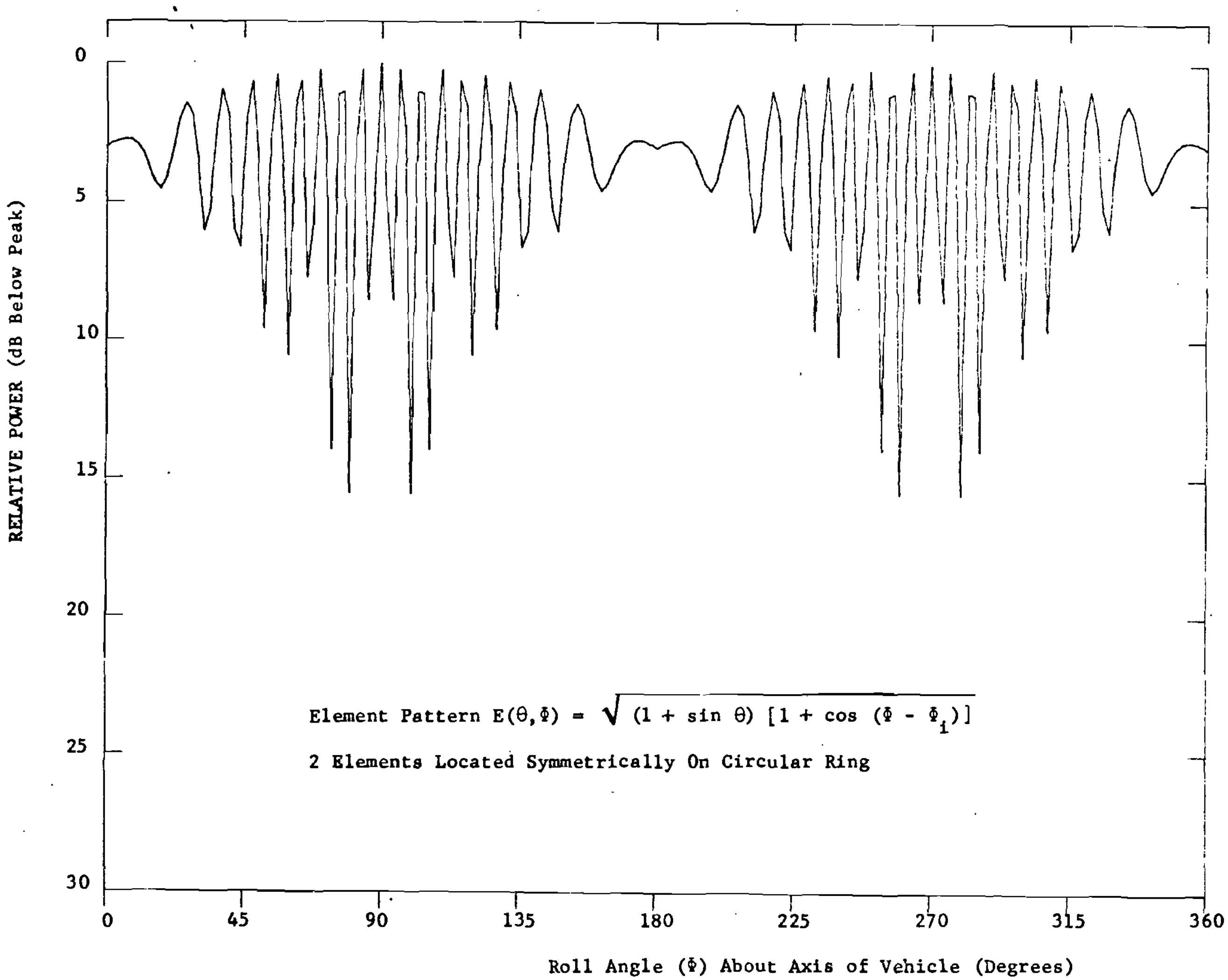


Figure 29. Calculated radiation pattern in the $\theta = 90^{\circ}$ plane from an array of 2 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

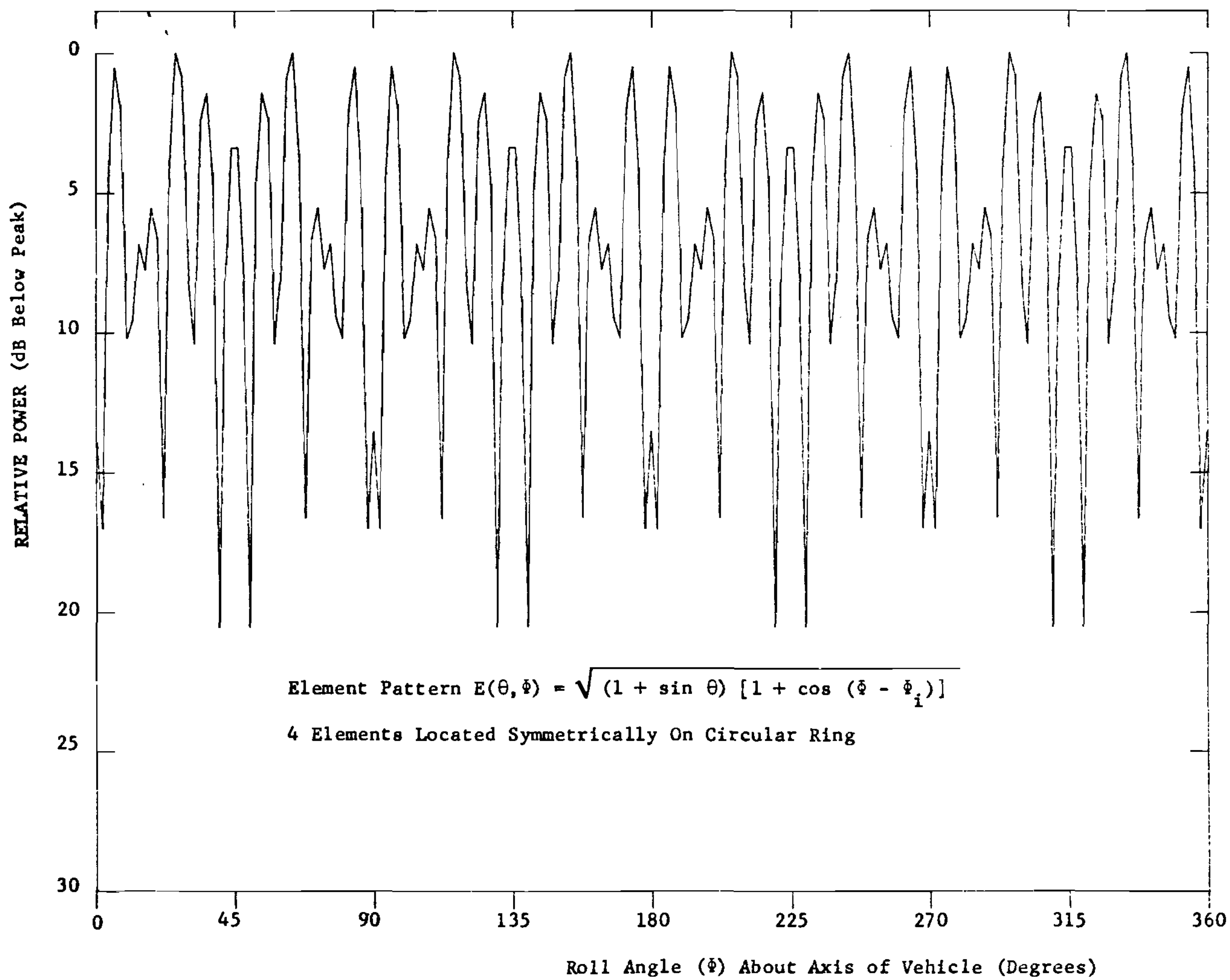


Figure 30. Calculated radiation pattern in the $\theta = 90^{\circ}$ plane from an array of 4 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

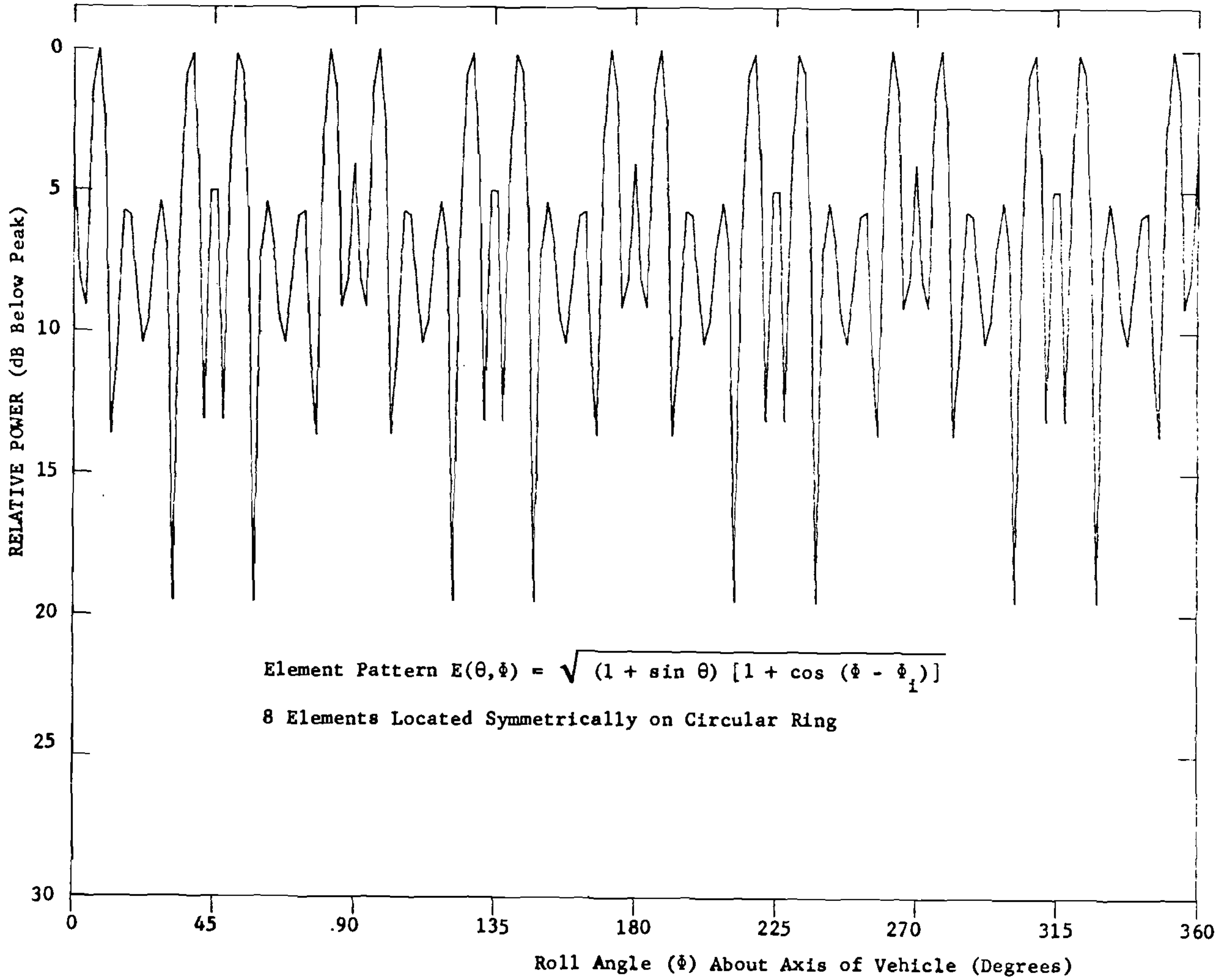


Figure 31. Calculated radiation pattern in the $\theta = 90^{\circ}$ plane from an array of 8 elements equally spaced on a circular ring of 7.2-inch diameter and operating at a frequency of 1600 MHz.

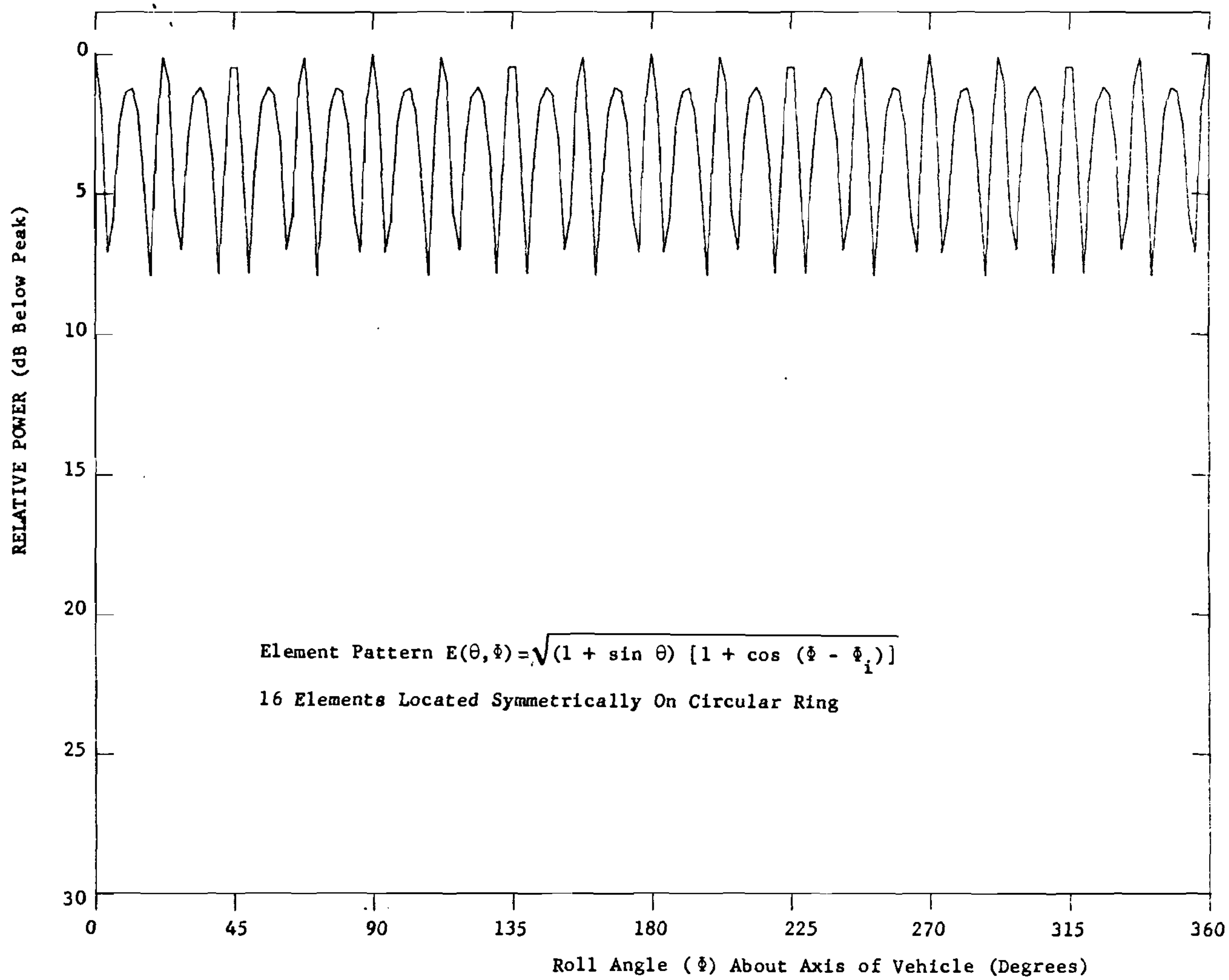


Figure 32. Calculated radiation pattern in the $\theta = 90^{o}$ plane from an array of 16 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

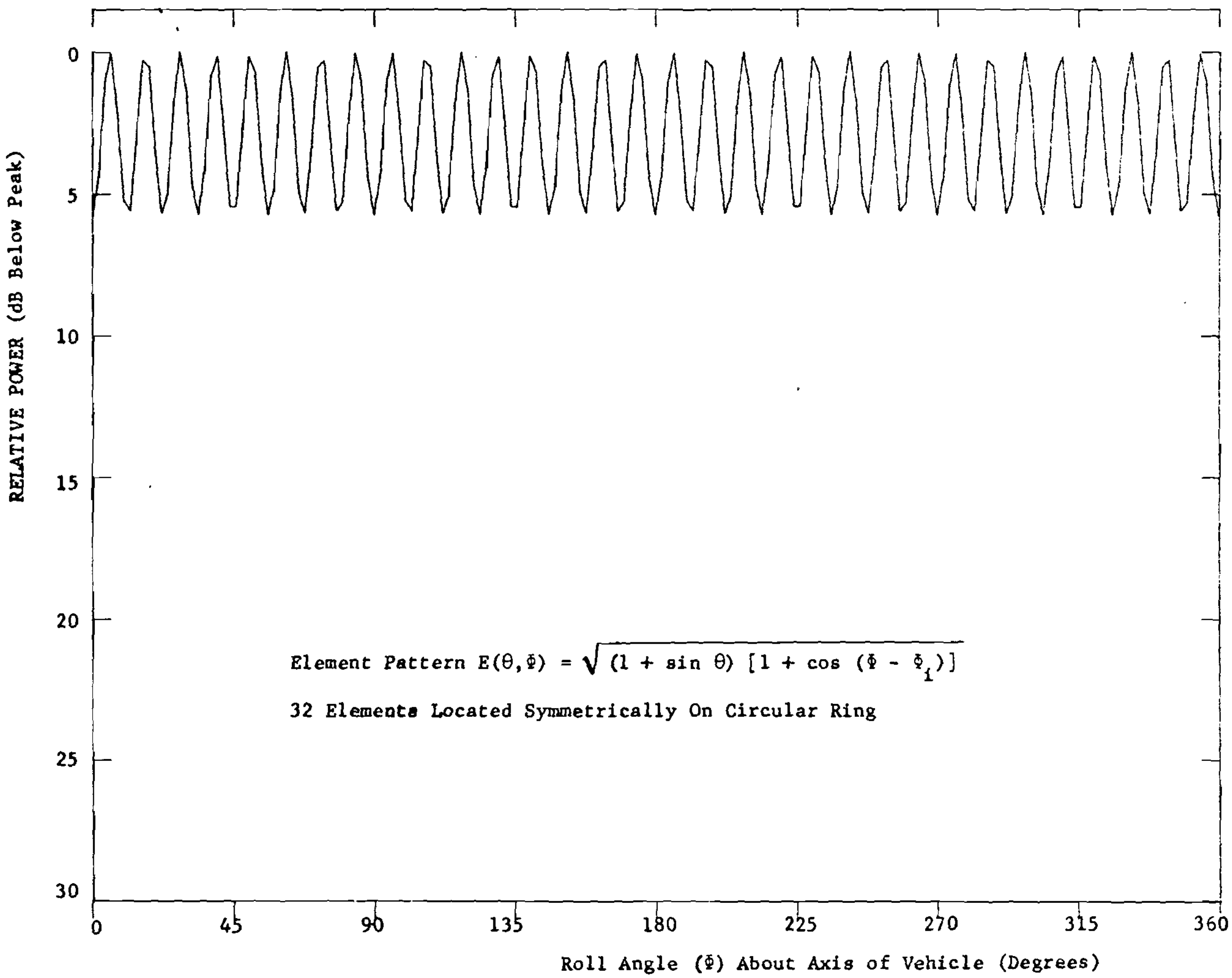


Figure 33. Calculated radiation pattern in the $\theta = 90^{\circ}$ plane from an array of 32 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

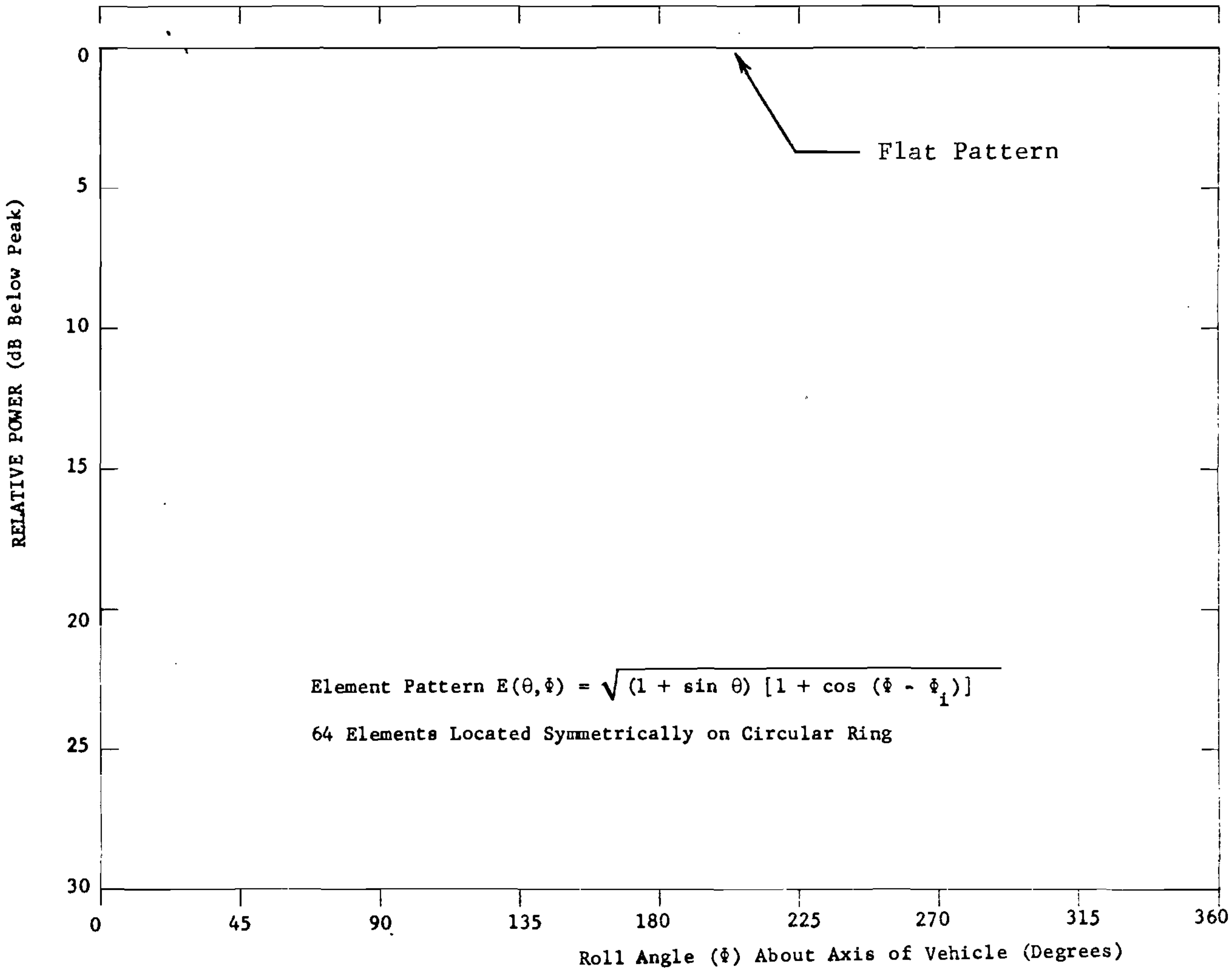


Figure 34. Calculated radiation pattern in the $\theta = 90^{o}$ plane from an array of 64 elements equally spaced on a circular ring of 72-inch diameter and operating at a frequency of 1600 MHz.

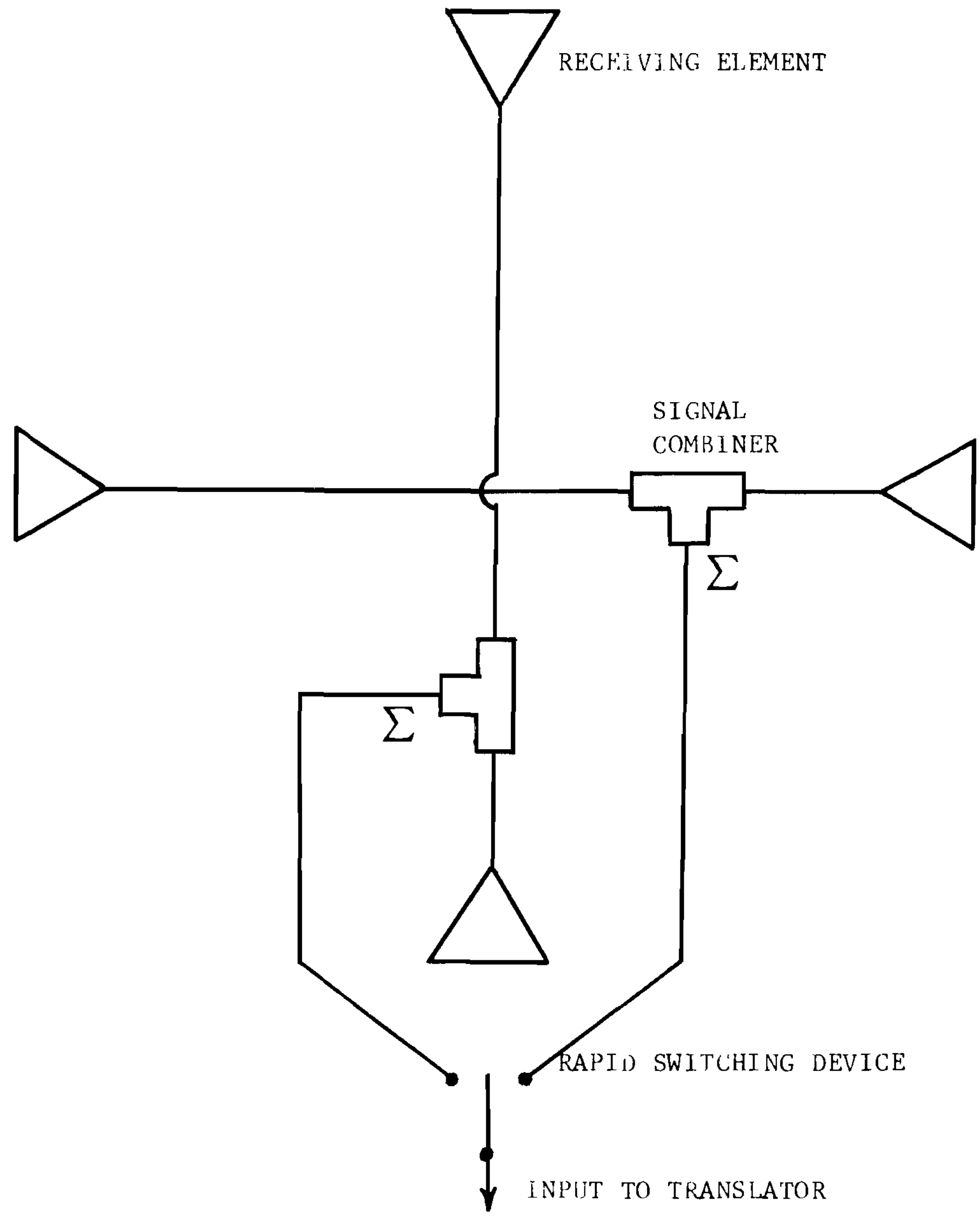


Figure 35. Simplified diagram of two-channel time diversity scheme for eliminating nulls due to rf addition.

logic behind such a scheme is that a two element array will most likely exhibit an interferometer effect at an angle half-way between the pointing angles of each of the elements which corresponds to the direction of maximum power radiated by one of the orthogonally placed elements; consequently, the orthogonal pair would be chosen. This scheme should in general raise the overall coverage and reduce the number of phase discontinuities.

Phase patterns (with the center of the vehicle as a reference) were calculated for one and two element arrays and are shown in Figures 36, and 37, respectively. At first glance, both of these cases appear equally poor; however, it should be noted that these contain a very large slowly varying term due to fact they are referenced to the axis of the vehicle and not the element itself. For the particular geometry and frequency at hand, this variation may be shown to vary as

$$\psi(\Phi) = 1756^{o} \, (1 - \cos \Phi) \tag{6}$$

where Φ is the azimuthal angle about the roll axis. The time rate of change of this function is given by

$$\frac{d\psi}{dt} \equiv 1756^{o} \sin [\Phi(t)] \; \frac{d\Phi(t)}{dt} \quad , \tag{7}$$

$$\psi'(t) = 1756^{o} \, w(t) \sin [\Phi(t)] \; , \tag{8}$$

where w(t) is the roll rate of the missile. The two-element phase patterns of Figure 37 were calculated again with the geometric term of Eq. (6) subtracted out for each element in the region where that element dominates. This new pattern is shown in Figure 38 to have an element interaction phase that is near constant except in the region halfway between the two elements where the orthogonal pair would be chosen anyway. Phase variation starts to occur at about 45^{o} rotation and the variations increase to a maximum value of about $\pm 45^{o}$ near 90^{o} of rotation.

From the above data, the time division multiplexing scheme offers superior pattern and phase performance over coherently added system. Indeed, both the

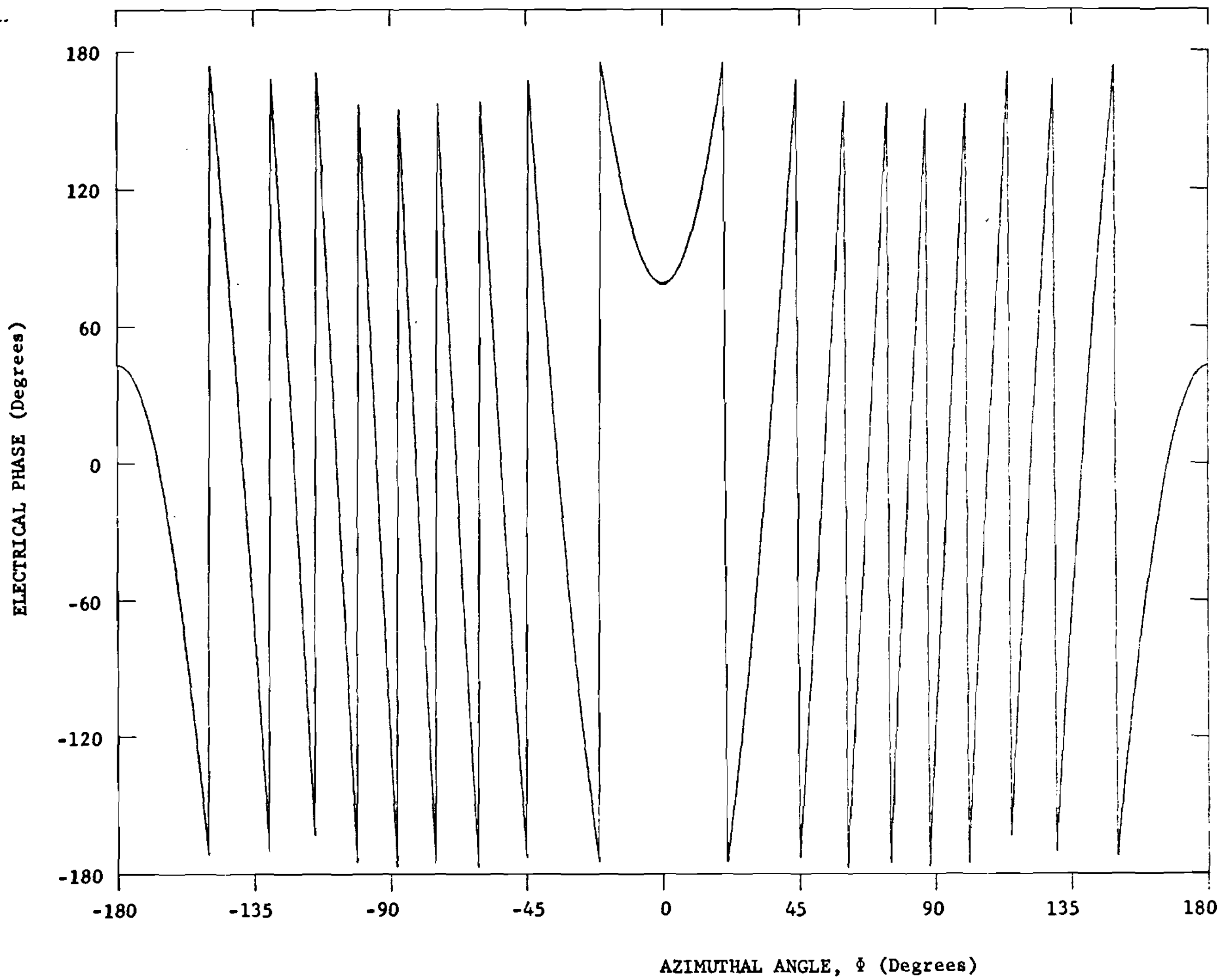


Figure 36. Calculated (scalar) far-field phase of the radiation from one cardioid element located on the SATRACK vehicle and operating at 1600 MHz.

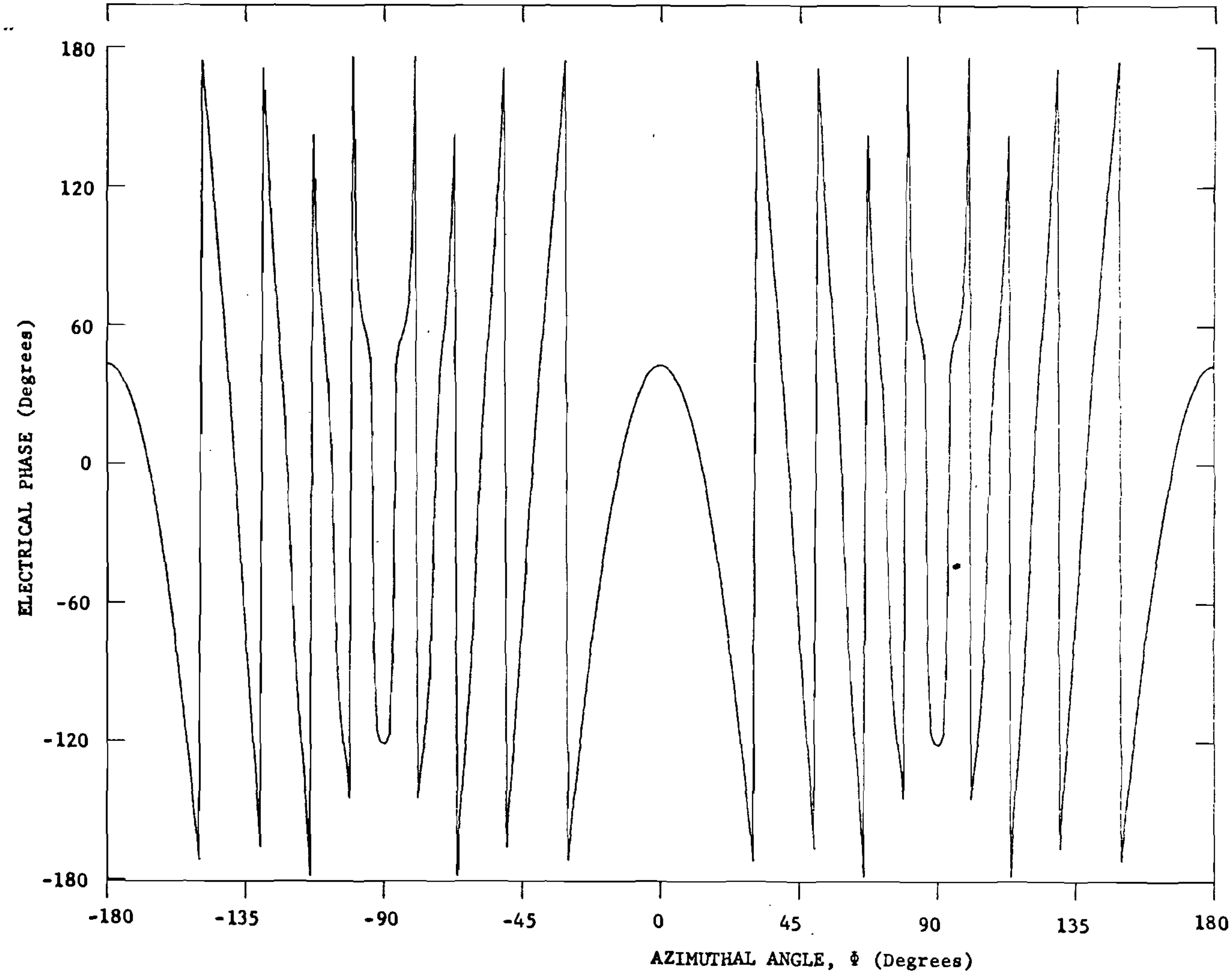


Figure 37. Calculated (scalar) far-field phase of the radiation from two diametrically opposite cardioid elements located on the SATRACK vehicle and operating at 1600 MHz.

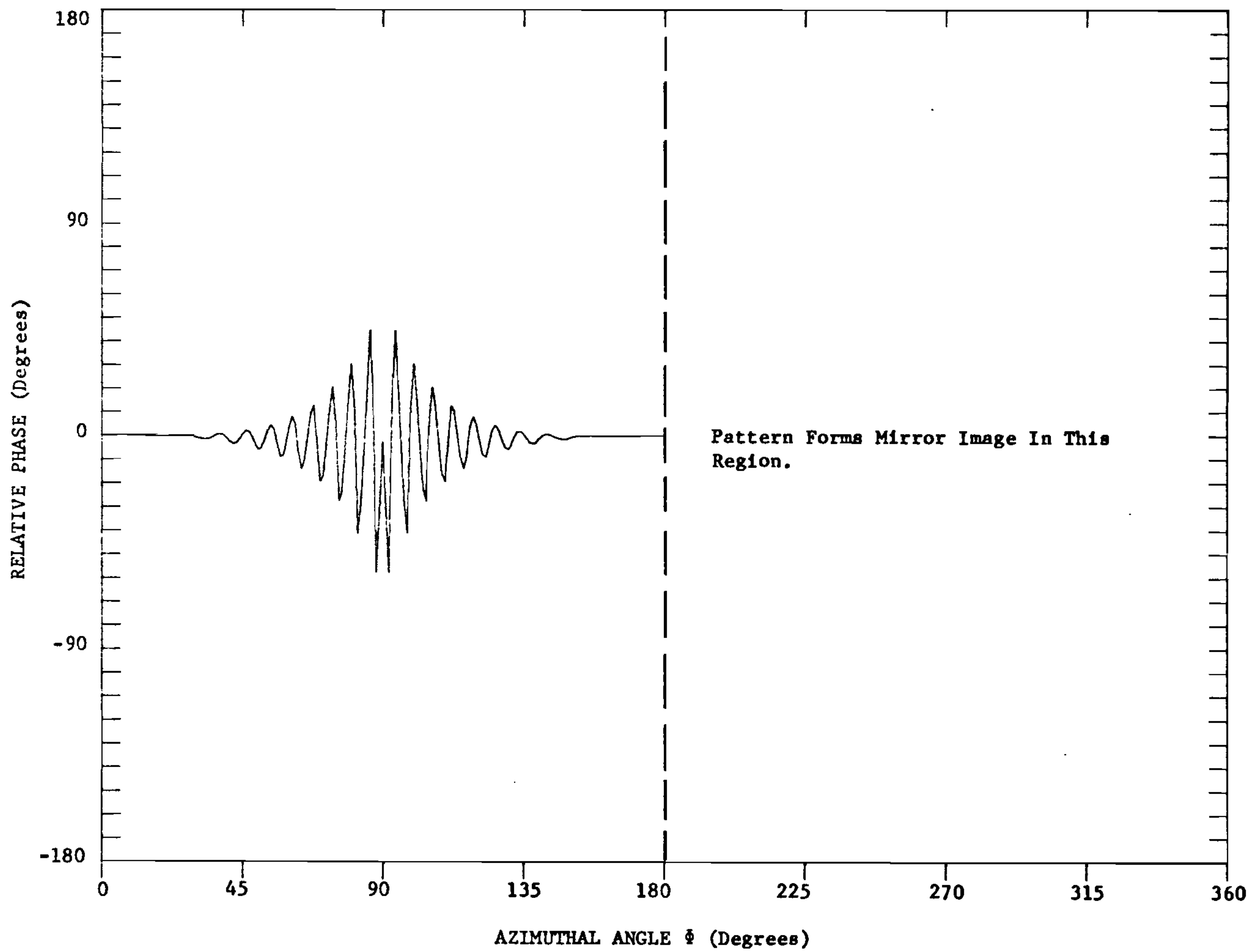


Figure 38. Calculated (scalar) far-field phase of the radiation from two diametrically opposite cardioid elements located on the SATRACK vehicle and operating at 1600 MHz. The large sinusoidal variation due to the rotation of the elements has been removed.

missile-borne and ground station hardware is somewhat complicated in going to this scheme; however, the alternatives are (1) an extremely large number of elements with a complicated and expensive feed network or (2) a small number of elements with their attendant multitude of pattern nulls and phase discontinuities.

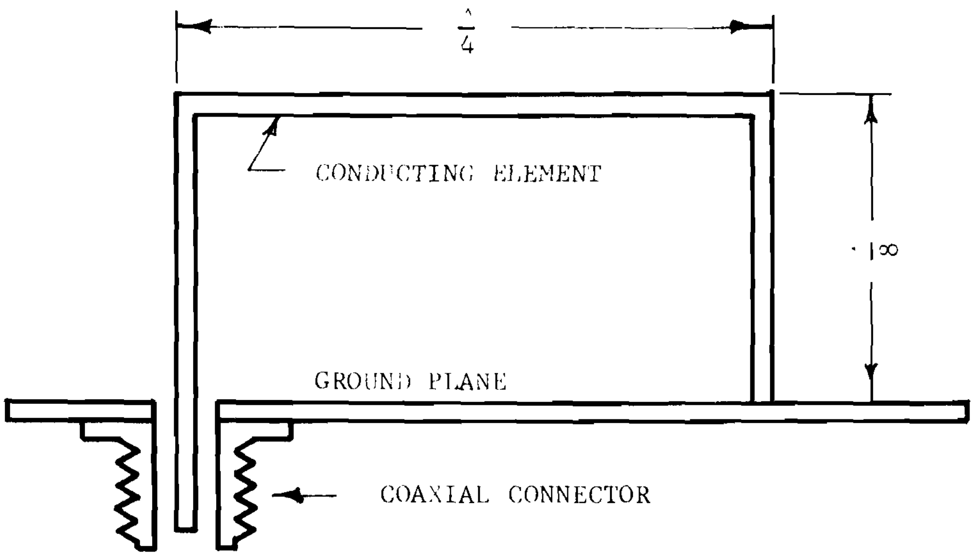
VI. SURVEY OF CANDIDATE ANTENNAS

Several candidate antennas appear attractive for application at one or both of the frequencies of interest. A list of those candidates which are felt to be applicable to SATRACK system are listed below.

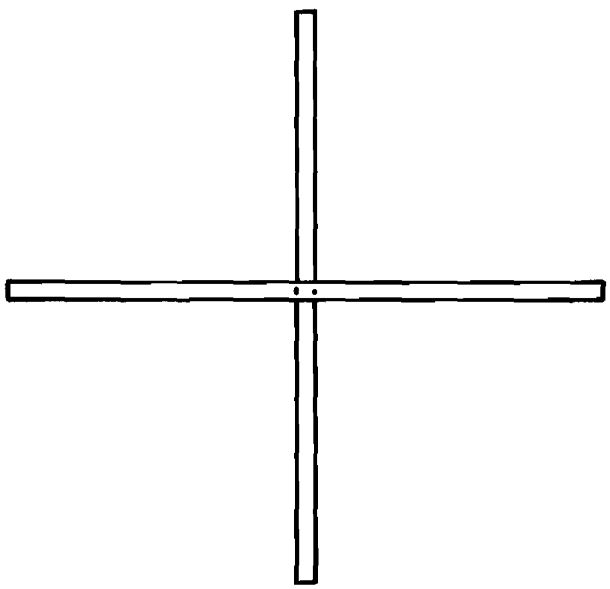
(1) Spiral
(2) Half-Wave Loop
(3) Crossed Dipoles
(4) Quadrafilar-Helix
(5) Microstrip Patch Radiator
(6) Microstrip Wraparound
(7) Cavity-Backed Slot

The flat spiral, which is felt by Georgia Tech to be the prime candidate for application at 1600 MHz, has a fairly broad beam and offers circular polarization. However, one of the strongest points in favor of the spiral is its long use as a laboratory instrument, thereby making it readily available off-the-shelf without design, fabricating and testing costs. At 1600 MHz, a spiral would be about four inches in diameter and three inches deep. The fine tuning process usually associated with narrow-band missile antennas is eliminated since spirals typically cover a 4:1 bandwidth. The log conical which is a three-dimensional extension of the spiral was not given separate treatment in this section since it merely offers increased bandwidth and requires more space (depth) on the vehicle. The spiral is not as attractive at 400 MHz since a diameter of approximately ten inches would be required. A somewhat smaller spiral could be used but with a corresponding loss in gain. If space were available for say an eight-inch spiral and the loss in gain were no more than 3 or 4 dB, then the possibility for dual frequency (400 and 1600 MHz) operation is extremely attractive.

The half-wave loop over a ground plane (see Figure 39 (a)) is a magnetic element which provides a reduction in the surface area required on the vehicle since part of its length is included in the vertical standoffs perpendicular to the ground plane. The length of each section of this element is adjusted so that the image of the horizontal section provides maximum reinforcement straight ahead. Also, if two such elements are



(a) Single Element - Side View



(b) Dual Crossed Elements - Top View

Figure 39. Schematic diagram of half-loop over a ground plane showing (a) side view of a single element and (b) top view of dual crossed elements for generating circular polarization.

placed orthogonally in space as shown in Figure 39 (b) and fed with a 90° time difference, the resulting pattern will be circularly polarized over a large portion of the hemisphere and the element coupling will be minimized. The bandwidth of the antenna may be increased by using a "thick" element. At 400 MHz, these elements would be about 7.4 inches long and 3.7 inches above the ground plane.

A pair of crossed dipoles offer a flat radiating surface and circular polarization (if phased correctly). However, the elements should be approximately one-half wavelength long which is about fifteen inches at 400 MHz. This number is too large to fit in the available space without end loading or element bending. The elements could be bent along an arc or into the shape of a swastika with a resulting reduction in size and an improvement in the circularity of the polarization; however, such attempts are merely approaching the spiral but without its inherent bandwidth.

The performance of the quadrifilar helix is well documented in the literature [3], [4], [5], [6] as a small, broad-beam, circularly polarized radiator. This element, however, tends to require more depth, which is also at a premium on the vehicle, than many of the other candidates.

The microstrip patch radiator similar to the one discussed in Section III.E. is attractive as a single element in that it can be made extremely thin and lightweight and can have circular polarization as one of its modes. The bandwidth of such an element is extremely narrow and the spatial distribution of its far-field beam is not well documented.

The microstrip wraparound radiator which can be thought of a continuum of the previously mentioned patch radiators is very attractive from a coverage standpoint since it can produce a pattern approaching omnidirectional in the roll plane. The wraparound radiates linear polarization, however unless it is segmented into a large number of patch radiators and fed properly (at the corner of each element). Calculations have shown that approximately 64 feed points or individual patches would be required at 1600 MHz for the SATRACK geometry. The chief drawback to the whole wraparound concept is that it must wrap completely around the vehicle or across areas where propulsion devices or other antennas have already been placed.

The cavity-backed slot has found long service as a missile antenna element since it may be made compact and has a broad beam. The slot suffers, however, from the face that it is narrowband and linearly polarized, although crossed slots may be fed so as to produce circular polarization.

After consideration of the above listed characteristics, it is felt that the spiral and the crossed half-wave loop are the prime choices for application on the SATRACK vehicle.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. Summary of Results

This report documents the significant results of a SATRACK missile antenna study performed for the Applied Physics Laboratory by the Sensor Systems Division of the Georgia Tech Engineering Experiment Station. The study was basically divided into three areas of interest according to frequency, namely 150, 400, and 1600 MHz. Significant findings in each of these areas are summarized below.

150 MHz

The investigations at 150 MHz were mainly concerned with pattern calculations, analyses of Lockheed data, and element breadboarding. It is recognized that this frequency is no longer of vital interest to SATRACK; however, it is felt that the techniques and significant findings should be documented.

Pattern calculations were performed by both scalar and moment methods as each offered certain advantages. The scalar analysis indicated that either of three different arrays could provide adequate coverage. These were (1) the two-element array with relative element phasing of $(0^\circ,0^\circ)$, (2) the four-element array with phasings $(0^\circ,0^\circ,0^\circ,0^\circ)$ and (3) the four-element array with phasings $(0^\circ,90^\circ, 180^\circ, 270^\circ)$. The moment method later illustrated that the four-element array with relative phasings $(0^\circ,0^\circ,0^\circ,0^\circ)$ was actually the best, and in fact produced coverage levels very near those measured by LMSC on their four-element array.

Georgia Tech performed computer analyses of LMSC's interim two-element and four-element arrays. The results of Tech's analysis was identical to that of LMSC and verified the fact that the four-element array was adequate.

Several 150-MHz patch radiators were fabricated and tested. These breadboard models indicate that very thin lightweight antennas can be made to operate at two independently-controlled frequencies. The elements are extremely narrowband and may have different radiation directions for each of the frequencies.

400 MHz

At 400 MHz, radiation patterns were calculated using scalar and moment methods. The scalar calculations indicate that both two and eight elements are superior in coverage to four elements; however, even these arrays performed considerably below the specification. The moment calculations showed that two, eight, and sixteen elements were again superior to four, but even these were inadequate. These figures are not intended to prove that better performance cannot be obtained at 400 MHz since it is very difficult to analytically model the vehicle there; however, they do indicate that a serious design problem is at hand. Any possibility which can improve this situation, such as circular polarization or time diversity, should be considered. A survey of candidate antennas was performed and some of those listed are applicable to 400 MHz. In particular, the crossed half-wave loop is compact and is capable of circular polarization.

1600 MHz

Patterns were calculated only by scalar methods at 1600 MHz due to the computer storage and time requirements of the moment methods. Amplitude pattern calculations indicate that between 32 and 64 elements would be required to eliminate pattern ripple in the roll plane and thereby increase the coverage. Phase patterns were also calculated when it was learned that APL was considering a four-element, two-channel, time-diversity scheme for eliminating nulls due to rf addition. These calculations illustrated the interferometer effect for each of the two element array is restricted to the region halfway between the two elements where the orthogonal array would be chosen anyway. The data contained in this report seems to indicate that time diversity offers improvement in coverage. The hardware required is indeed complicated; however, the alternatives are either a large cumbersome array or a small array whose pattern is filled with nulls and phase discontinuities. The survey of antennas listed several antennas which have application to 1600; however, the flat spiral is recommended since it is circularly polarized, small, broadbeam, and commercially available.

B. Recommendations For Future Activities

This report corresponds not so much to a breakpoint in the technical work being performed as it does to the end of a contractual period. Several technical problems still loom, and a list of some of these to which Georgia Tech can make a significant contribution are listed below.

(1) An in-depth analysis of the antennas which appear to be prime candidates for application at 400 and/or 1600 MHz

should be performed. The spiral appears attractive for 1600; however, such a factor as exact coverage obtainable needs further study. From a size and polarization viewpoint, the crossed half loop is a strong candidate at 400 MHz. Models of such an antenna are currently being built and tested at Georgia Tech. The goal of this effort is to develop two pairs of crossed loops (one each at 400 and 1600 MHz) over the same ground plane. The smaller 1600 MHz pair is nested beneath the 400 MHz pair.

(2) Although it is known that the new time diversity system will provide increased coverage, the coverage levels to be expected are not known. The computer programs already developed are equally applicable to this situation as to the coherent rf addition system and should be applied.

(3) All pattern calculations reported here indicate that the 400 MHz problem will not be easily solved by a multi-element array; consequently, the feasibility of using time diversity at 400 MHz should be considered.

(4) A limited vehicle impedance mock-up should be fabricated to test the elements currently being tested at Georgia Tech.

(5) The computer analysis of the LMSC paper tapes should be continued as these tapes become available.

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APPENDIX I.

RADIATION SPECIFICATIONS FOR SATRACK

150-MHz AND 400-MHz MISSILE-MOUNTED ANTENNAS

1.0 SCOPE

This specification covers the design, development and performance testing of the 150 MHz and 400 MHz missile-borne antenna systems for the SATRACK system. This specification includes a probabalistic description of the antennas' radiation characteristics and the method by which these characteristics shall be measured and documented.

1.1 DESIGN OBJECTIVES

The SATRACK Antennas shall be designed to provide pattern coverage and absolute gain levels which are deemed by APL to be compatible with satisfactory overall system performance and which are more specifically outlined in Section 2 (REQUIREMENTS) below.

2.0 REQUIREMENTS

2.1 ITEM DEFINITION

The SATRACK antennas are defined as all of those devices which are concerned with the reception, matching, and combining of the 150 MHz and 400 MHz antennas and shall include all portions of the signal path down to the point where these signals pass into the transponder.

2.2 ELECTROMAGNETIC RADIATION PERFORMANCE CHARACTERISTICS

The electromagnetic radiation specifications of the two subject antennas take the form of the percentages of a 4π steradian sphere over which the gain (in dB) with respect to a circularly polarized isotropic antenna is greater than or equal to the levels listed below for each antenna.

Antenna	Minimum Received Power Level Over 90% of a 4π Steradian Sphere
150 MHz	-13
400 MHz	-10

3.0 QUALITY ASSURANCE PROVISIONS

3.1 GENERAL

The contractor (LMSC) shall conduct as a minimum the tests described herein to establish and document that the resulting antenna hardware complies with the performance specifications of Section 2.0.

3.2 RADIATION TESTS

The contractor shall record and document the radiation distribution over a complete 4π steradian sphere in increments of not greater than 2^{o} in both θ and φ, where θ and φ are the standard orthogonal coordinates of a spherical coordinate system, when the antenna is used as a receiving antenna illuminated by a circularly polarized transmitter. The relative levels recorded shall be given absolute values by substituting a circularly polarized reference antenna, having known gain with respect to an isotropic radiator, for the test antenna, thereby assigning absolute gain levels to at least two points on the measured radiation distribution plot. This data shall be documented in the standard rectangular θ - φ contour format provided by commercially available radiation contour plotters and shall also be documented in a manner suitable for input to a digital computer for calculation of the relative portions of the complete sphere over which the absolute level is greater than or equal to the level specified in Section 2.2.

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Under Subcontract 600128, Task 2 with The Applied Physics Laboratory of The Johns Hopkins University, the Engineering Experiment Station at the Georgia Institute of Technology has performed an antenna design study in support of the Navy's SATRACK program. Investigations,

both theoretical and experimental, were directed toward achieving omni-directional coverage from the SATRACK vehicle at the frequencies 150 MHz, 400 MHz, and 1600 MHz. Typical calculated coverage levels for several different arrays are included along with a survey of applicable element types.

Several breadboard microstrip patch radiators were fabricated and tested in an effort to develop a lightweight, dual-frequency element.

A time-diversity system proposed by APL and LMSC was analyzed, and the results are included herein.